MICROLITHOGRAPHIC FABRICATION OF RF COILS FOR NMR MICROSCOPY

BY

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THESIS

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WE HEREBY RECOMMEND THAT THE THESIS BY

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THE DEGREE OF MASTER OF SCIENCE

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O-517

I would like to dedicate this thesis to my parents, Paul and Lorelei Weiss.

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1. INTRODUCTION

The goal of this project is the fabrication of planar microcoils on a glass substrate using photolithographic techniques. These microcoils will be utilized as radio frequency (RF) receiver coils in microscopic nuclear magnetic resonance (NMR). Small feature fabrication, such as that obtained with photolithography, will reduce the size of these coils by at least a factor of 10 compared to current RF receiver coils. Microcoils are defined as coils with diameters smaller than 10 mm. Electrical characterization of the microcoils was performed to measure their resistance, capacitance, and inductance.

Published results of NMR experiments with RF coils in the microcoil domain were presented as early as 1966.[1] These early microcoils were solenoidal with diameters of several millimeters. These coils provided improved filling factor, that is, the fractional volume of the coil occupied by the sample, and also enhanced the sensitivity for small volume samples. More recently, Cho et al. obtained 15 μm in plane resolution with microcoils with diameters ranging from 1 to 14 mm.[2] Zhou et al. along with Professor Paul Lauterbur reported using a 2.9 mm diameter microcoil in conjunction with a 10 G/cm gradient field to obtain the highest resolution in NMR microscopy to date.[3] The small resolution obtainable in microscopic NMR has been instrumental in the observation of small biological processes. For example, Russell Jacobs and Scott Fraser of the California Institute of Technology describe a novel NMR system utilizing a magnetic field that is 10 times stronger than clinical instruments, which provides a million times better resolution. The system can be used to observe the movements of cells of developing embryos.[4] Another difficulty encountered in NMR is obtaining three-dimensional data for NMR microscopy. Zhou et al. have overcome this difficulty by addressing the low signal-to-noise ratio (SNR) inherent in high resolution microscopy and utilizing novel methods to compensate for the low SNR.[5]

The problems associated with microscopic NMR can be described as a poor SNR. Work done by Peck et al. has indicated that the creation of planar coils with lithographic techniques would be the next step in extending NMR microscopy to smaller samples.[6] Since the signal detected by an RF coil is directly proportional to the sample volume, decreasing the size of the RF detection coils should increase coil sensitivity by providing better coupling between the coil and the sample. Although many factors (e.g., relaxation processes, free and restricted diffusion, and localized susceptibility variations) must be considered when examining small samples, a primary limitation in NMR microscopy is a poor signal-to-noise ratio (SNR). Peck has done work with wire-wound solenoidal coils and shown that an enhanced SNR is achieved when using these coils (50 μm - 1000 μm in diameter).[7] He presented a theory in which further reduction in the size of coils, as well as the correct coil dimensions to optimize SNR, such as inner turn spacing equal to turn line width, should further enhance the SNR.

As background, the SNR for a microcoil in a configuration where the sample is excited by a 90° RF pulse can be approximated as [8,9]

$$\mathrm{SNR} \propto \frac{(B_1/i)\,\upsilon_s\,\omega_o^2}{V_{noise}} \qquad (1)$$

The term ω_o is the precession frequency which is related to the static magnetic field strength by the Larmor equation ($\omega_o = \gamma\,B_o$). The sample volume of interest is represented by υ_s, and the RF magnetic field per unit of current of the receiver coil is represented by (B_1/i). Both the Nyquist noise from the coil conductor and the noise induced in the system from a lossy sample are represented by the term V_{noise}. For microcoils, the coil noise, which remains relatively constant for a decreasing coil size, dominates V_{noise}.[2,8,10] In view of Eq. (1), it is clear that a reduction from 10 mm^3 to 10 μm^3 of υ_s corresponds to a signal loss of 10^9. This loss in signal is due to a reduced number of nuclear spins contributing to the signal. To compensate for this reduction in

SNR, high static field magnets and/or small RF coils can be used. It is for this reason that smaller microcoils are sought.

The lithographic techniques used to fabricated the microcoils are similar to those techniques used in the fabrication of semiconductor devices. In fact, the tools and methods are the same; however, modifications have to be made to compensate for different materials used in the processing. Microelectronic fabrication involves techniques similar to those used to create printed circuit boards, but on a smaller scale. Features as small as 1 μm can be created using conventional optical lithography (also called photolithography). Working at such small levels requires the use of another medium to help transfer the desired pattern onto the substrate. That transfer medium is photoresist (PR). Photoresist is a thin film spun onto the surface of the substrate which contains a photoactive element. When ultraviolet light comes in contact with the PR, the PR is chemically altered. It is this alteration which allows the patterning of the medium. A developer is used to selectively remove PR from the surface. In the case of positive PR, the exposed regions are removed; in the case of negative PR, the unexposed regions are removed, and in the case of image reversal with positive PR, the regions exposed during a second exposure are removed.[11] The PR now acts as a mask protecting the final pattern, while the area under the windows is etched. The PR could also act as a mask to allow selective deposition onto the surface of the substrate.

The use of fabrication techniques for biological applications is not new. David Stenger has combined microelectronic fabrication techniques and novel surface chemistry to layout patterns of molecular soil, encouraging the selective growth of cells.[12] Novak and Wheeler, and Boppart et al. have also used these fabrication techniques to create microelectrode arrays on glass substrates to measure neural potentials.[13, 14]

The concept design of the microcoil was a planar spiral coil with the width of the coil turns the same as the width of the spaces between the turns. The feature sizes of the coil turns were intended to range from 1 - 5 μm. The inner coil diameter was intended to be as small as 10 μm, but could be made as large as 135 μm for the purpose of optimizing the model parameters. For testing, i.e., measure R, L, and C for modeling fitting, the contact pads had to have a 150 μm center-to-center spacing. The substrate was intended to be glass of sufficient thickness to provide a rigid substrate. The insulating material between layers was intended to be thick enough so that the area inside the coil, that is, the inner diameter area, could be etched away. This would allow the placing of the NMR sample with its center level with the coil turns, which would provide better coupling between the sample and the magnetic field of the microcoil. This insulating material was originally planned to be PR or a polyimide, which can be spun onto the substrate several μm thick. The conductor material was to be of a sufficiently low resistance material. Aluminum and gold are common conductors used in microelectronic processes. Testing was done to fit the microcoils to the model in Fig. 1. The components L, R, and C represent the typical linear RLC model of inductors, where C determines the self-resonance value. This self-resonance should be away from the region of interest, that is, while using a frequency in the MHz range, a self-resonance in the GHz range would be acceptable. Note that the Q of the microcoil is determined by R, L, and ω ($Q = \omega L / R$). The remaining terms in the model represent the coupling transmission line where LP1 and CP1 represent one side and LP2 and CP2 represent the other side.

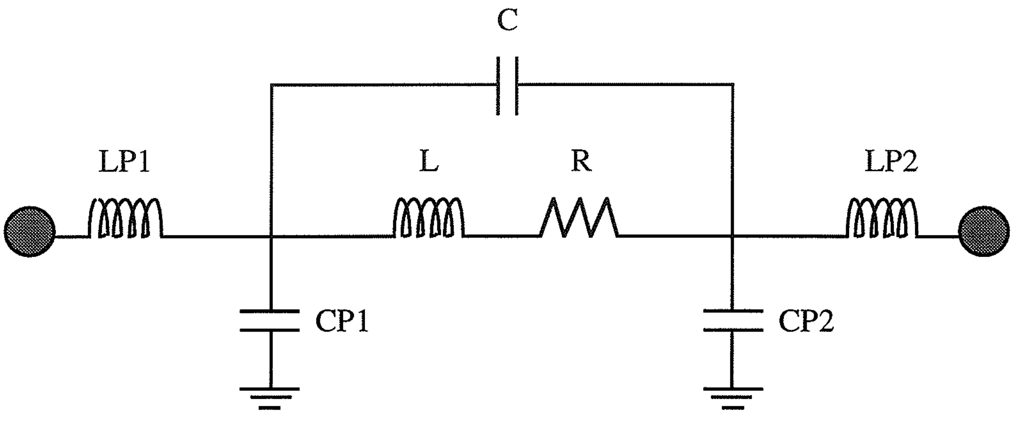

Fig. 1 Microcoil Model

2. METHODS

A planar microcoil of the type described would have to be created on a substrate. A glass substrate provides rigidity. The glass is also a good insulating material and is nonferromagnetic. Since one of the goals of the project was to image biological cells, a glass substrate would help facilitate compatibility with biological research. The glass substrate is soda-lime mask glass (3 X 3 X 0.062 in^3) cut into squares (1 X 1 X 0.062 in^3). The mask glass (Hoya) was used to ensure a flat substrate. As with typical printed circuit board creation, warping of the substrate (circuit board) creates problems. The other materials required for the fabrication of microcoils include: an electrically conductive material and an electrically insulating material. The electrically conductive material should have a low resistance. This resistance adds to the V_{noise} in Eq. (1). The electrically insulating material should provide shielding for the contact pads from the magnetic field of the coil, as well as electrical insulating of the contact pads from the coil turns, except through the via holes.

The fabrication of microcoils begins at the stage in which the concept design is drawn on a computer-aided design (CAD) system. The design implementation may vary from the concept design for a number of reasons. For example, there may be limitations imposed by the CAD system on the shape and size of devices. The CAD program used in this process is the Layout System for Individuals (LASI) written by Dr. David Boyce (GE / RCA / Harris). This drawing is transferred to a mask plate. Please see Appendix B for information concerning the mask making process. Once the mask has been made the design can be transferred to a substrate. The transfer may take more than one process sequence depending on the complexity of the design. Once the transfer is complete, the design can be tested in an appropriate manner. Any design flaws can be rectified with modifications, creating a new design implementation, that is, returning to beginning of the flow chart. This process flow is illustrated in Fig. 2. The rectangles describe the action, and the ovals contain the equipment and/or process necessary to implement the action.

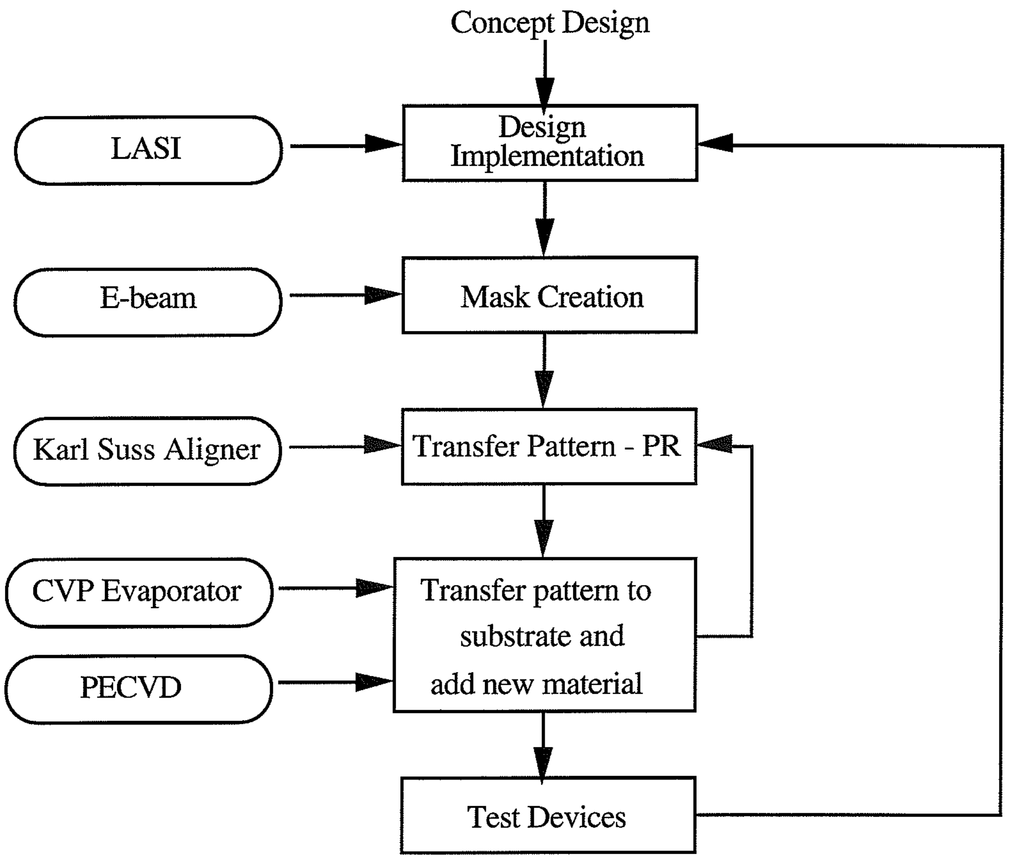

Fig. 2 Process Flow Diagram

Microcoils are created using optical lithographic techniques. There are three mask levels, two for metal deposition and one for patterning the insulator. One mask plate contains all three mask levels, each one taking up a quadrant of the plate. Each level of the mask is approximately 1 in^2. The substrate material is soda-lime mask plate glass (Hoya). The chrome coating is removed from 3 in^2 soda-lime mask plates which are subsequently scribed into 1 in^2 pieces. The first level of processing creates the coil turns, the second level opens the via holes in the insulating layer, and the third level creates the contact pads. Titanium (Ti) is deposited prior to the gold (Au) to provide a metal/metal bonding surface. Silicon dioxide is used as the insulating layer. The second metal layer is also Ti/Au. Figure 3 illustrates the top and side views of each level of processing for one part of a coil.

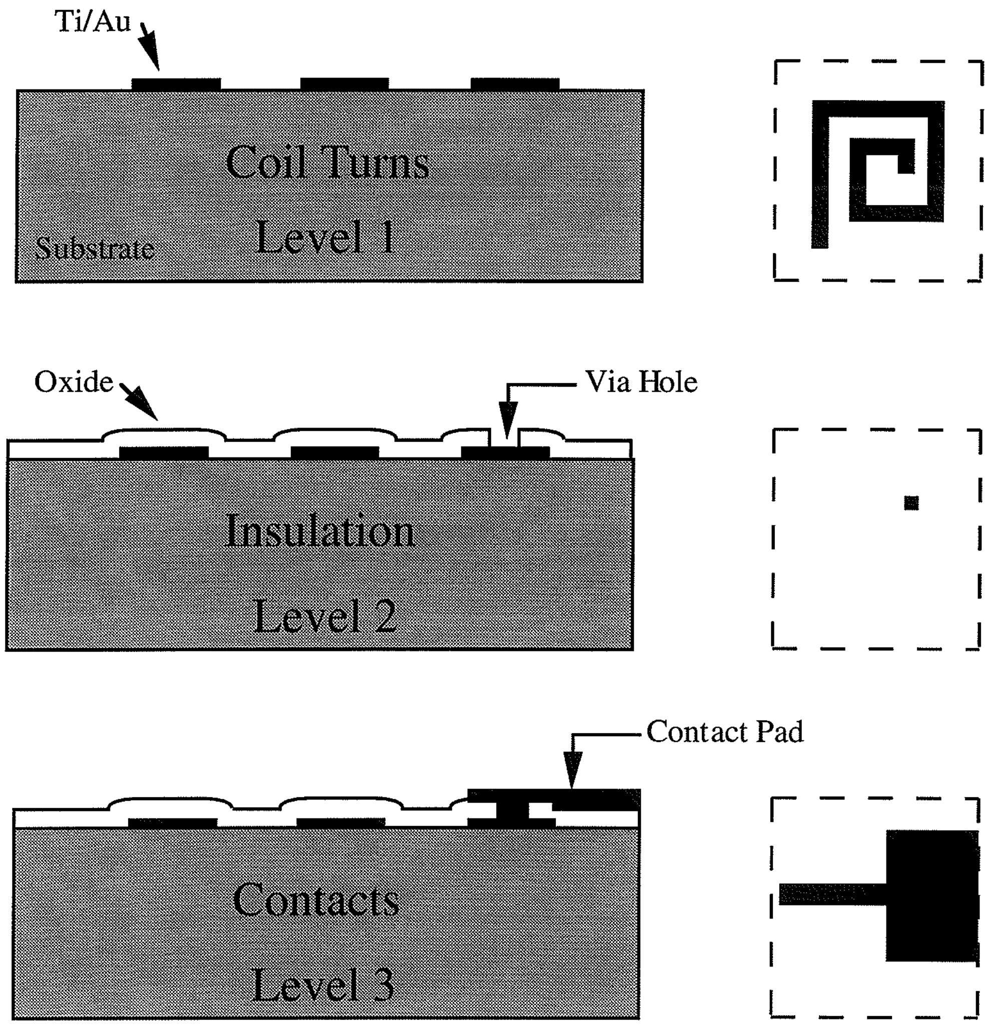

Fig. 3 Side and Top Views of Processing Steps

A complete description of each processing step in given in Appendix A. In general, the processing consists of a cleaning process to remove particulate material (described in Appendix A). A typical set of processing steps is; (a) a bakeout to remove water from the substrate is done at 100°C for 5 min, (b) spinning of AZ5214 (Hoechst Celanese Corporation) positive PR onto the substrate at 4500 rpm for 30 sec, (c) softbaking the PR to drive out more moisture and harden the surface of the PR is done at 100°C for 90 sec, (d) exposure of the PR is done with a 320 nm UV source, and (e) developing the PR with MF327 (Shipley). An optional plasma oxygen descum can be done before further processing to ensure complete removal of any PR residue. An oxygen plasma will remove organic material from the surface. A 1 min descum is sufficient to remove any PR residue. Incomplete PR removal could impede further processing steps because the required window might not be completely opened. For this process, incomplete removal would mean that during the oxide etch to open the via holes, the entire hole might not be opened, that is, the PR residue acts as a mask to the oxide underneath. See Fig. 4 for an illustration of this effect. The substrate is now ready for an etch or an evaporation, i.e., transfer of a pattern into material or selective placing of the material onto the substrate in the desired pattern. After the etch/evaporation step, the PR is removed, i.e., stripped from the substrate, with acetone. At this point, material needed for the next step can be grown or deposited. See Fig. 5 for the specific modification of this process description for each of the three levels on the mask.

Material can be patterned with an etch or via lift-off. For etching, material to be patterned is deposited or grown onto the surface of the substrate; PR is then spun on and patterned. This pattern is then transferred to the material by using an acid to selectively remove the exposed areas. Alternatively, lift-off could be used. For lift-off, PR is spun on to a sample and patterned first; then material is evaporated on to the substrate bonding with the substrate only in the open areas (see Fig. 6). However, for lift-off the PR must have the correct profile for the method to work properly. The profile required for lift-off is one in which there is no direct line of sight between the top surface of the PR and the PR/substrate interface. This will ensure that there is no physical

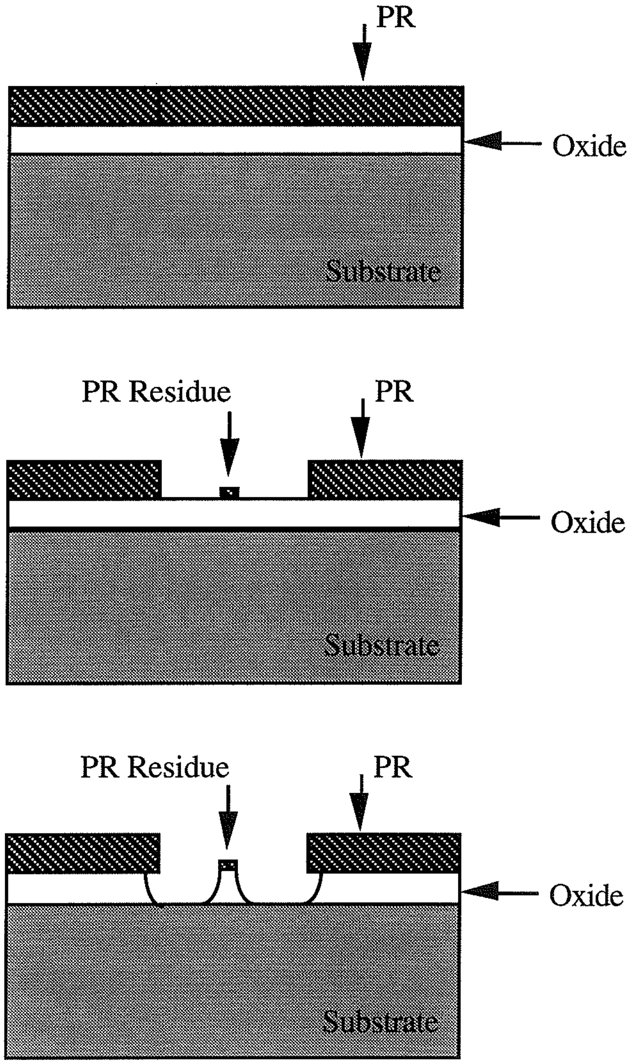

Fig. 4 Effect of PR Residue on Etching

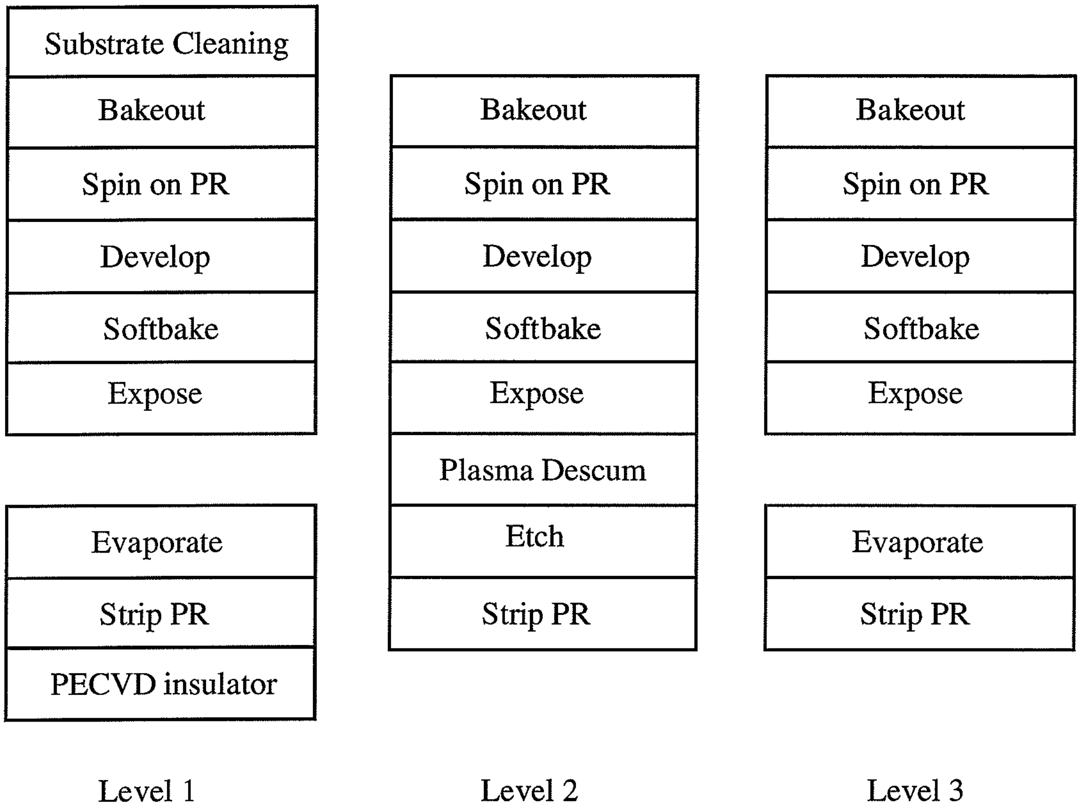

Fig. 5 Process Steps for Each Mask Level

connection between the metal on the top surface of the PR and the metal on the substrate. If there is a physical connection, either the metal will rip and the metal on the substrate will remain (possibly with a 1 μm tall piece of metal standing at the rip sight) or all of the metal will be removed when the PR is removed. After development the desired substance can be deposited. If done correctly, the material will bond with the substrate only in the areas without PR. The remaining material on top of the PR will be removed when a solvent removes the PR. The profile of the PR must be one such that the line of sight from the air/PR interface to the PR/substrate interface is clear. This ensures that there is no physical connection between the material which has deposited on top of the PR and the material which has been deposited on the substrate. It is also helpful if the PR thickness is greater than the thickness of the desired deposited layer.[15] The thickness of the PR is determined by the type of PR and the conditions used to spin it onto the substrate, specifically, the time and speed of the spin. The PR is spun onto the substrate under a spinner hood. The substrate is placed on a chuck and held in place with a vacuum. This process spins at 4500 rpm for 30 sec which results in a 1.2 μm layer of AZ5214.

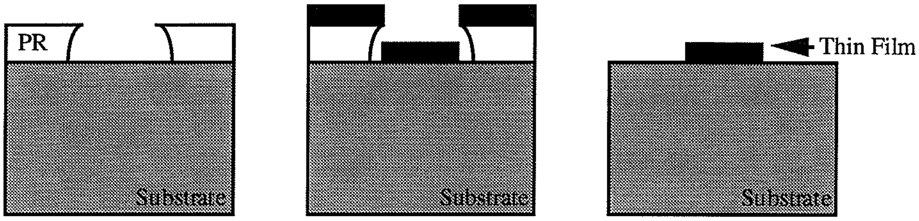

Fig. 6 Lift-off Illustration

There are two methods which can be used to create the correct profile needed for lift-off. Image reversal, which requires two exposures and a reversal bake, and a single exposure with a chlorobenzene dip. Image reversal is a method which can be used to transfer a negative copy of a pattern without using negative PR. The AZ5214, unlike most positive PRs, has an added ingredient which, after the reversal bake at 125°C, changes the initially exposed regions such that they are insoluble in the developer. A flood exposure is used to change the solubility of the remaining PR. The method is illustrated in Fig. 7. The reversal bake is especially sensitive to temperature. The time of the reversal bake should be sufficient to bring the substrate up to the reversal bake temperature and change the exposed regions to insoluble. For small features, i.e., 1 or 2 μm, it is difficult to transfer patterns this way reliably. Close contact is necessary during exposure. In this process, a darkfield mask is created by the e-beam. To use image reversal, the mask must be image reversed, i.e., make a lightfield mask, and then image reversal must be used with the lightfield mask to transfer the original pattern onto the substrate. The alternative method requires the use of chlorobenzene. Normal exposure, that is, one exposure is used to expose the PR; however, prior to development the PR is dipped in chlorobenzene. The chlorobenzene pulls

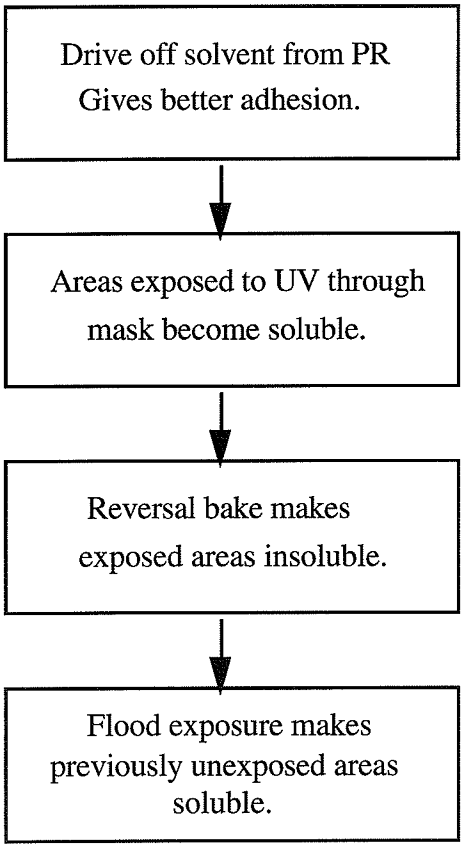

Fig. 7 Image Reversal

outs moisture from the surface of the PR, making it resistant to development. During development, the PR under the chlorobenzene develops away faster than the top layer, leaving an overhang, i.e., there is no line-of-sight between the top PR surface and the PR/substrate interface. See Fig. 8 for illustration of the effect of chlorobenzene on development which creates the overhang.

Testing of the coils from the mask designated NEWGEOM (these are the generation II coils) was performed with GGB picoprobes with 150 μm pitch over a frequency range of 1 - 50 GHz. The HP 8510 B network analyzer was controlled by an HP computer utilizing the Noise Parameter Test Software developed by Casade Microtech. The measured s-parameters were saved on floppy disk and converted using emd 2s 2p for the modeling program. The modeling program MDS uses the plotted data to optimize element values in the desired model. Figure 9 illustrates the modeling program operations.

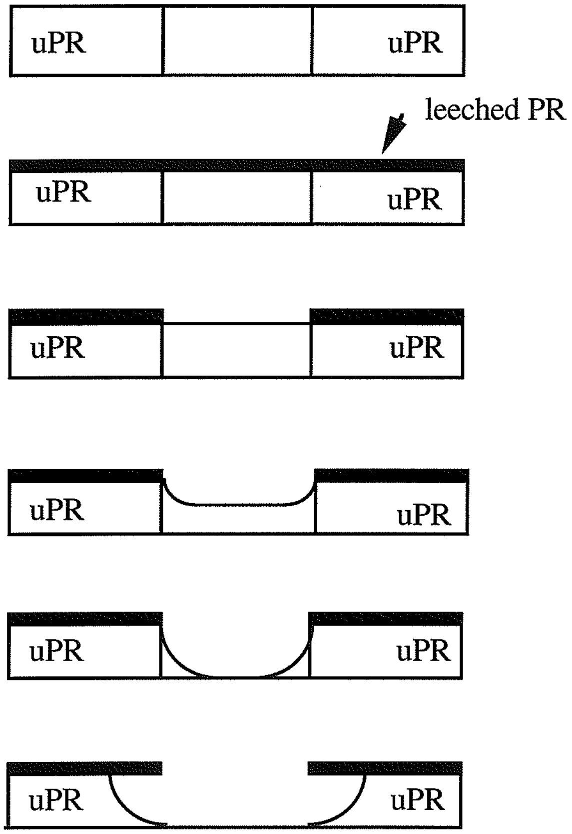

Fig. 8 Chlorobenzene Dip and Development

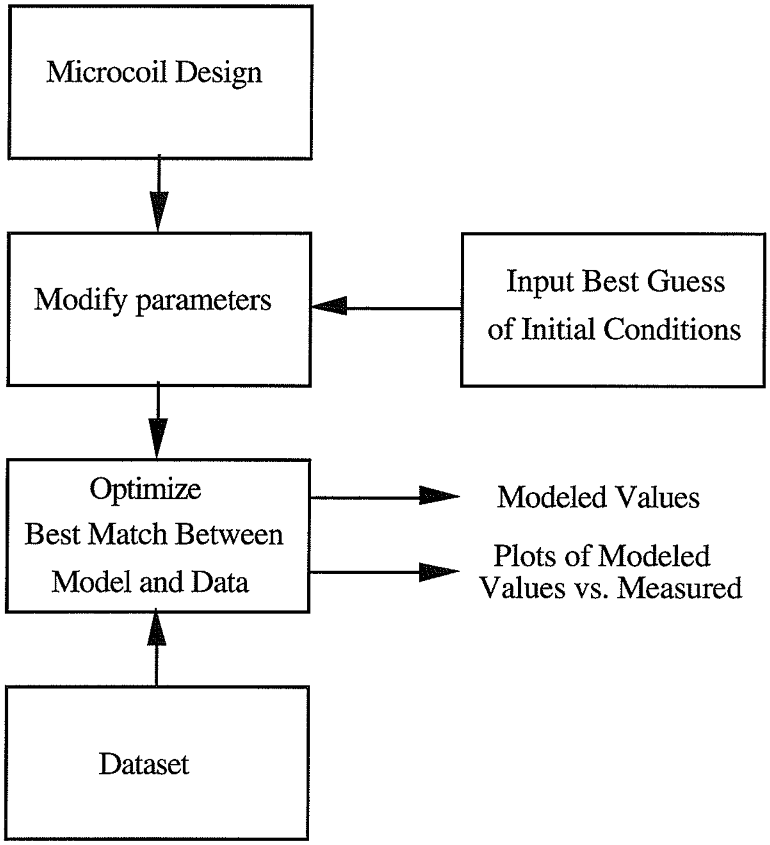

Fig. 9 Illustration of MDS Flow for Modeling

3. RESULTS

In the course of implementing the concept microcoil, three different mask designs were created. The first two, designated as PECK and MASK2 are considered generation I, proof of concept, microcoils. The coils generated from these masks were used to generate spectra, thus showing that the coils could be used for NMR spectroscopy. The spectra were generated via NMR spectroscopy using a GN-300 (7.05T) / 89 mm NMR spectrometer.[16,17,18] Connection was made to the coils via a 4 cm semi-rigid coaxial cable of 50 Ω with silver paint and gold bonding wire. A silicone rubber (RTV) sample was used to obtain the spectra. Coils from this generation had typical resistance values of 25 to 150 Ω and typical inductance values of 1 to 10 nH. Some of the relevant mask and process parameters are displayed in Table 1. Fundamentally, PECK and MASK2 are very similar; however, to fabricate a device with several layers, alignment markers are necessary. These are located in the same relative location for each layer of the design and are in general rectangular shapes, one layer larger than the other to allow one to be placed inside the other. PECK had alignment markers only in the four corners of each level of the design, whereas MASK2 had nine alignment markers, eight along the edges and one in the center.

Table 1 Mask Parameters

Mask Plate Designation	Metal	Insulator Material	Coil Diameter Inner (μm)	Coil Turn (μm)	Contact Pad Width (μm)	# of coil turns
PECK	Al	PR	10 - 200	1 - 5	75	3 - 25
MASK2	Ti / Au	silicon dioxide	10 - 200	1 - 5	75	3 - 25
NEWGEOM	Ti / Au	silicon dioxide	10 - 70.5	2 - 5	50	3 or 7

The second generation coils are found on NEWGEOM. (For an illustration of the generation II coil dimensions see Fig. 10 and see Fig. 11 for a generation I coil.) As mentioned previously, there are two different testing geometries. The relevant mask and process parameters are displayed in Table 1. Both geometries have the same parameters. The number of turns is either 3 or 7 to allow determination of the effect of the number of coil turns in future SNR measurements. The diameters vary as well as the width of the coil turns. Full use of this mask was not possible due to image reversal loss of the coils with 2 μm features. For the NEWGEOM mask, the one-port geometry is designated as geometry A (see Fig. 12) and geometry B (very similar to A), and the two-port geometries are designated as C (see Fig. 13) and D (see Fig. 14). For the two-port geometry, the conductor had to be moved occasionally to keep the spacing between the coil and the conductor equal; this is designated as geometry D, otherwise C and D are the same.

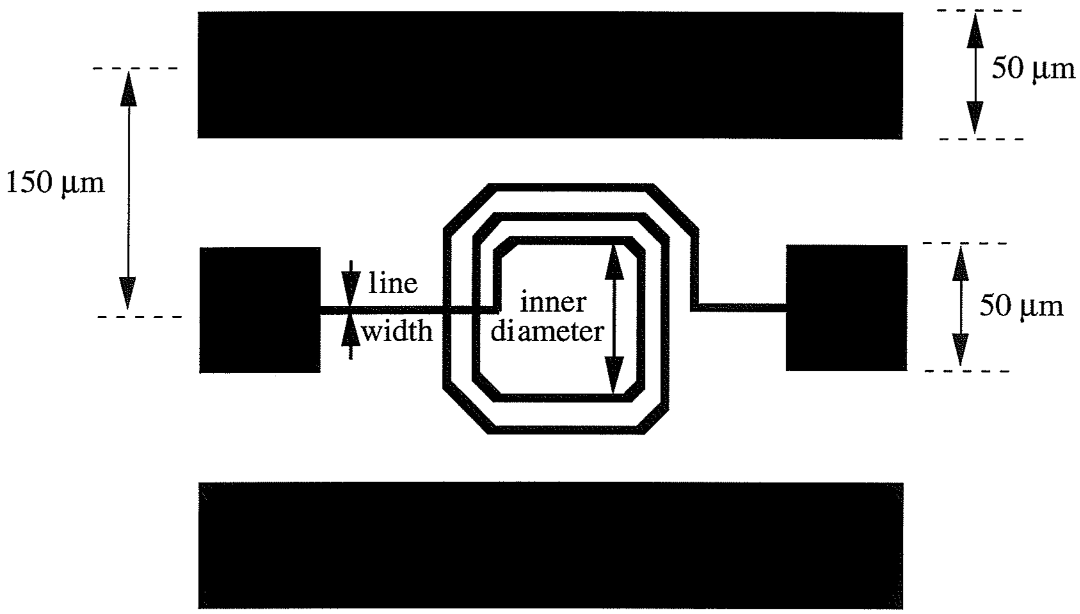

Fig. 10 Top View of Geometry C Showing Parameters

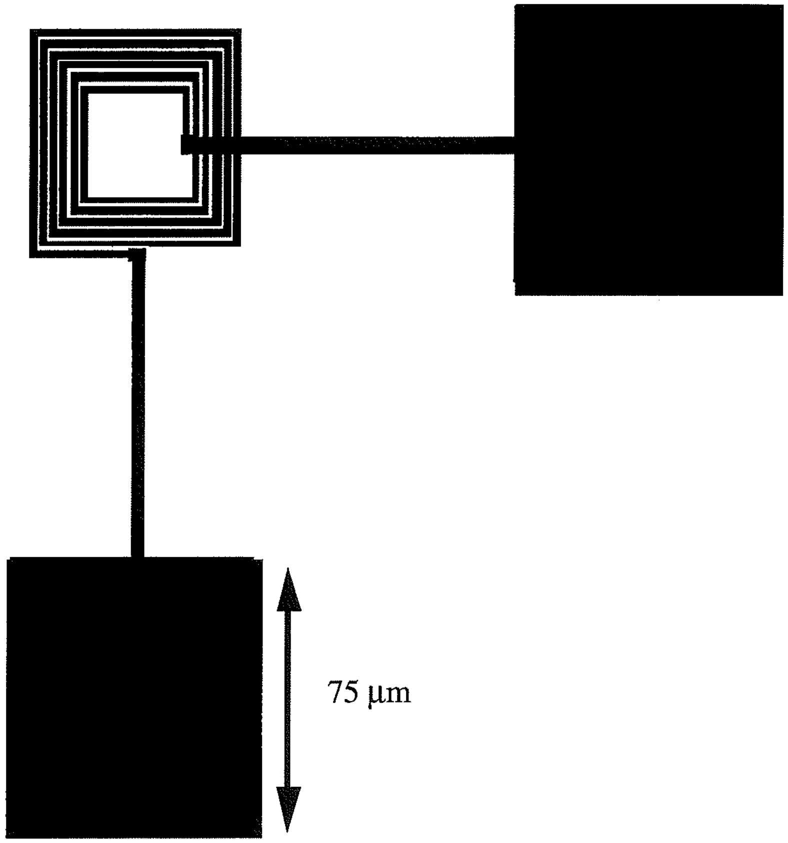

Fig. 11 Generation I Microcoil

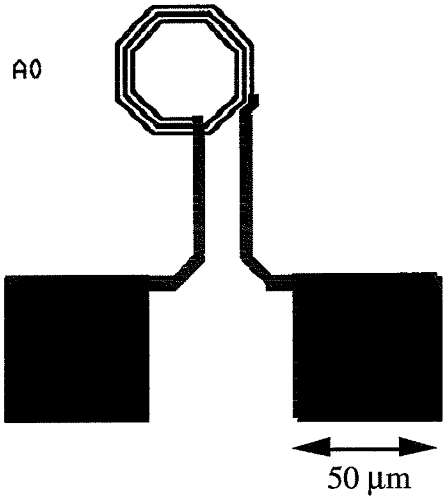

Fig. 12 One-Port Microcoil - Geometry A

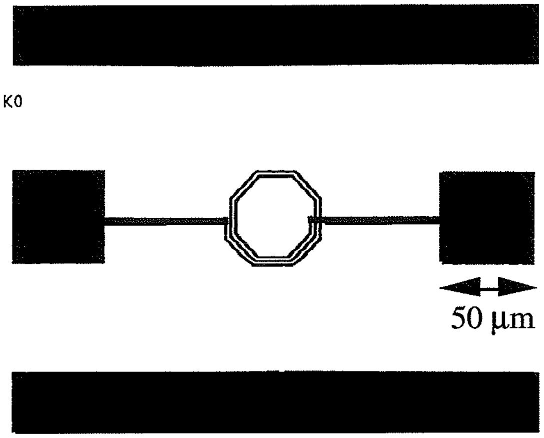

Fig. 13 Two-Port Microcoils - Geometry C

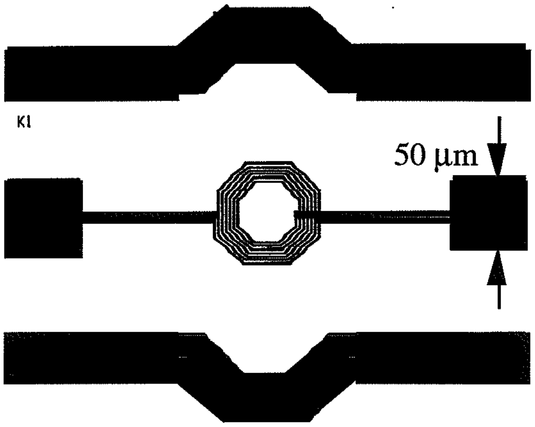

Fig. 14 Two-Port Microcoil - Geometry D

Of the generation I coils, the coils from PECK were fabricated using etching, since only one metal, Al, was used, and the coils from MASK2 were fabricated with lift-off, since two metals, Ti / Au, were used. To be able to produce devices with smooth edges with lift-off, it is necessary for the PR profile to be as shown in Fig. 6. A series of test samples were processed to establish the correct fabrication conditions. The results are shown in Figs. 15 16, 17, and 18. Each figure shows a side view of the sample profile that was obtained by processing the substrate, and then cleaving (breaking) it such that the profile could be examined.

The process technique evolved as a result of the need for the correct PR profile. While the chlorobenzene was being used, unsatisfactory profiles were observed. Figures 15, 16, and 17 illustrate the problem as well as show a control sample. The control sample has a Si substrate and is processed under the same conditions as those shown below for the glass substrate. The SEM micrograph in Fig. 15 shows a glass substrate at the first level of processing, the PR profile of coil turns prior to metal deposition, but after development for the following fabrication conditions:

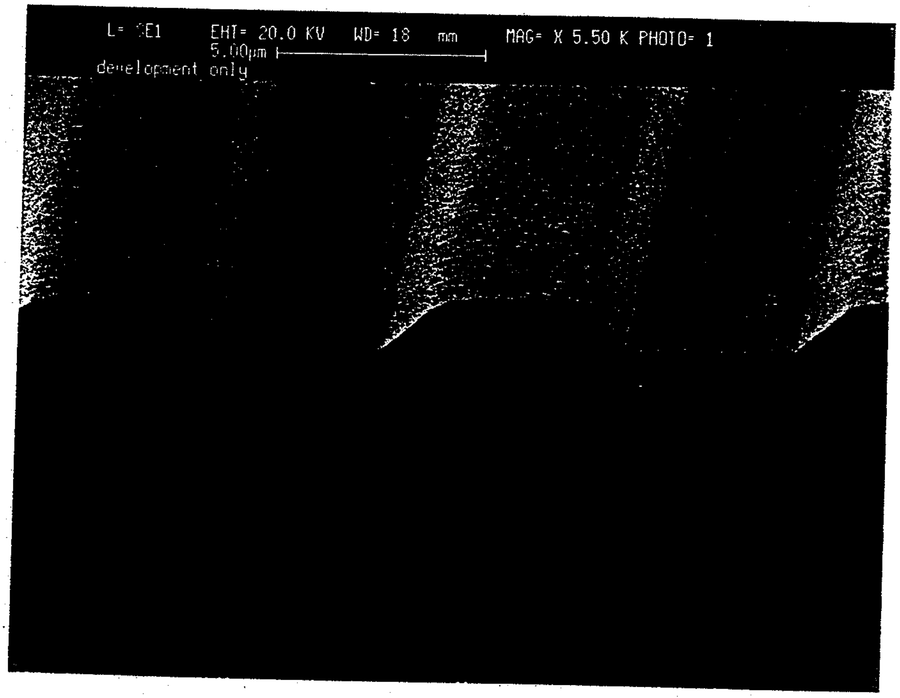

Fig. 15 Sample 102593E Level 1 PR Profile

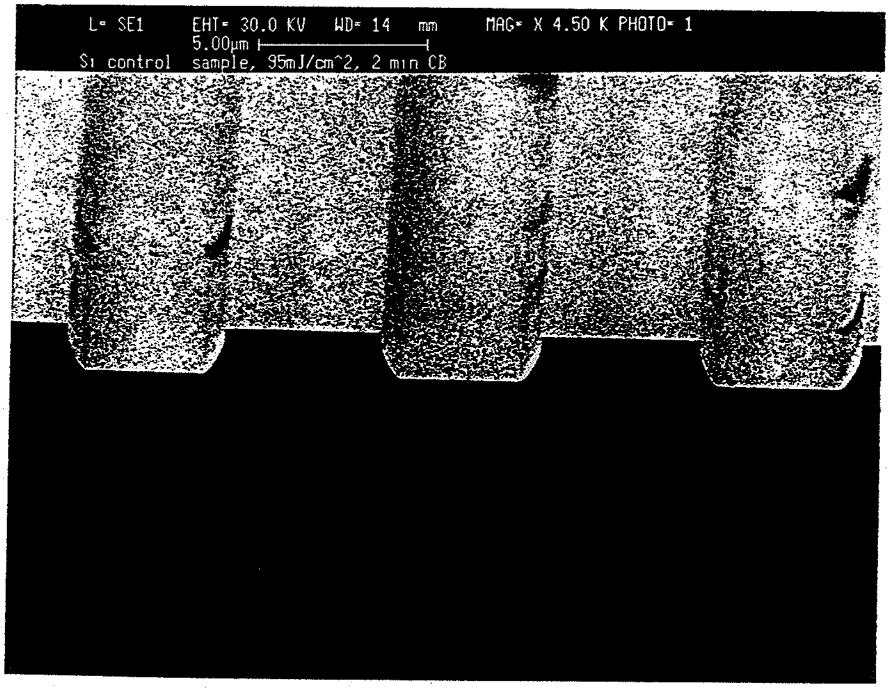

Fig. 16 Sample 111793-Si Control Level 1 PR Profile

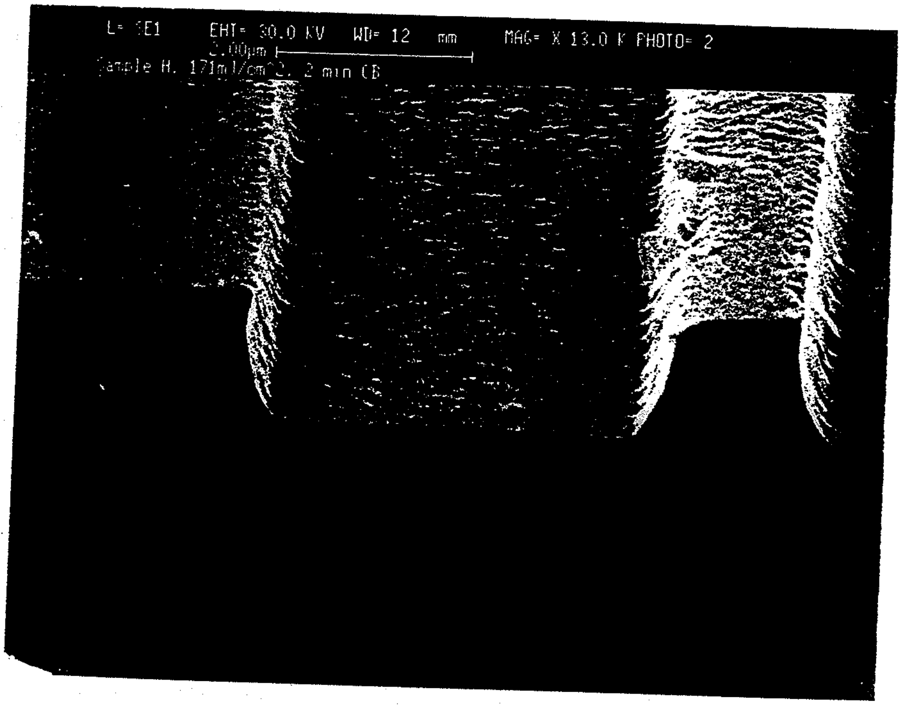

Fig. 17 Sample 111793H Level 1 PR Profile

1) Bakeout at 110°C for 5 min.

2) Spin AZ5214 at 4500 rpm for 30 sec.

3) Softbake at 110°C for 90 sec.

4) Expose for 10 sec.

5) Dip in chlorobenzene for 2 min at 30°C.

6) Develop in MF327 for 90 sec.

Note that the above procedure utilizes a chlorobenzene dip to achieve the lift-off profile. The SEM micrograph in Fig. 16 shows the same fabrication conditions for a Si substrate. Note that the PR profile is drastically different. The Si sample has the preferred PR profile, although the bottom of the PR did not receive a large enough dose. This result illustrates the difference in reflection for different substrates. Figure 17 shows the profile for another glass substrate at an increased exposure time of 18 sec (instead of 10 sec). Some overhang is seen here, but again, the profile is not ideal. Note that the bumps on the PR are an indication that either there is a problem with exposure or that an oxygen descum would be useful.

When the processing technique was altered to include image reversal instead of a chlorobenzene dip, the profile obtained was very similar to the Si control sample in Fig. 16. Again, the dose received by the PR at the interface needed some adjustment, but overall the profile is adequate. Figure 18 shows the SEM micrograph for a glass substrate at the first level of processing, the PR profile of a coil turn prior to metal deposition for the following fabrication conditions:

1) Bakeout at 110°C for 5 min.

2) Spin AZ5214 at 4500 rpm for 30 sec.

3) Softbake at 110°C for 90 sec.

4) Primary expose through mask plate for 90 sec.

5) Reversal bake for 90 sec at 125°C.

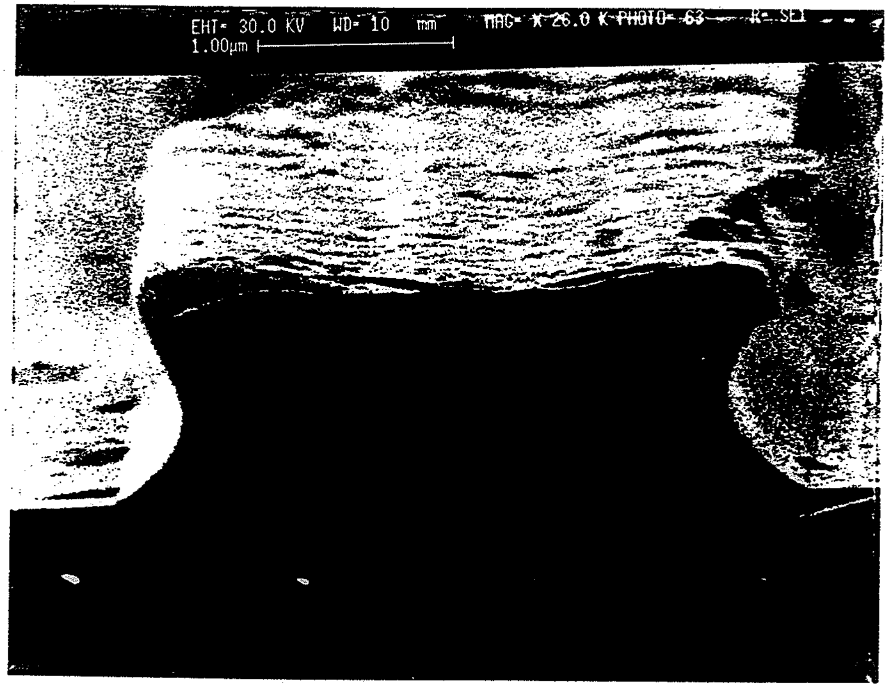

Fig. 18 Sample 123093A Image Reversal Level 1 PR Profile

6) Flood exposure for 45 sec.
7) Develop in MF327 for 90 sec.

Note that the above procedure utilizes image reversal to achieve the lift-off profile. It is with this processing technique that the microcoils were created for testing.

The generation II microcoils were tested and some of the data are shown for geometry C/D and A in Tables 2 and 3 and Figs. 19 and 20 for both the 3-turn and 7-turn coils for constant line width with varying diameters. The data for both the 3-turn and 7-turn coils for varying line width with approximately constant diameters are shown for geometry C/D and A in Tables 4 and 5 and Figs. 21 and 22. Now that the fabrication work is complete, the microcoils can be used in NMR microscopy to calculate SNR.

Table 2 Model Data for Varying Diameter : Two-Port

No. Turns	*Line Width (μm)*	*Diameter Inner (μm)*	*Geometry*	*lead L (pH)*	*paras C (fF)*	*main L (pH)*	*main R (Ω)*	*main C (fF)*
3	3	20	C	0.50	1.500	541	20.9	1.7
3	3	30	D	0.58	2.400	683	24.3	2.0
3	3	40	C	2.70	0.650	706	26.4	2.8
3	3	50	D	0.45	4.400	1000	34.5	1.9
3	3	60	C	0.43	1.500	1030	38.5	2.6
7	3	20	D	84	6.3	1190	118.8	20
7	3	30	D	220	7.7	2970	78.1	7.4
7	3	40	D	350	9.1	3440	88	9.1
7	3	50	D	240	10	4390	98.7	8.7
7	3	60	D	49	11	5570	127.1	7.5

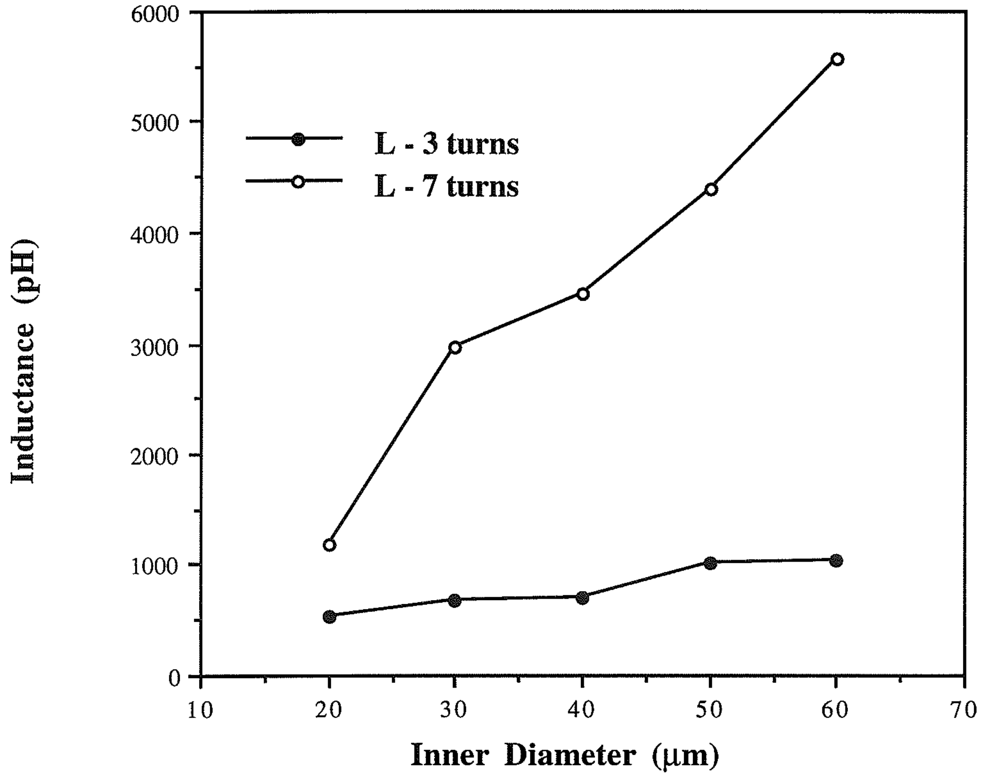

Fig. 19 Inductance vs. Inner Diameter for Two-Port Microcoils

Table 3 Model Data for Varying Diameter : One-Port

No. Turns	*Line Width (μm)*	*Diameter Inner (μm)*	*Geometry*	*lead L (pH)*	*paras C (fF)*	*main L (pH)*	*main R (Ω)*	*main C (fF)*
3	4	22.0	A	0.01	3.10	309	18.6	0.09
3	4	29.5	A	0.02	0.69	371	13.3	0.01
3	4	39.5	A	0.02	7.10	458	14.7	0.08
3	4	49.5	A	0.00	12.00	559	16.6	0.83
3	4	59.5	A	0.00	20.00	669	18.7	0.01
3	4	70.5	A	0.00	24.00	776	20.8	0.10
7	4	22.0	A	180.00	50.00	1500	36.9	0.00
7	4	29.5	A	320.00	57.00	1490	41.3	0.00
7	4	39.5	A	470.00	63.00	1580	44.8	0.00
7	4	49.5	A	570.00	67.00	1790	48.0	4.90
7	4	59.5	A	300.00	0.50	2760	51.6	75.00
7	4	70.5	A	570.00	43.00	2760	55.7	45.00

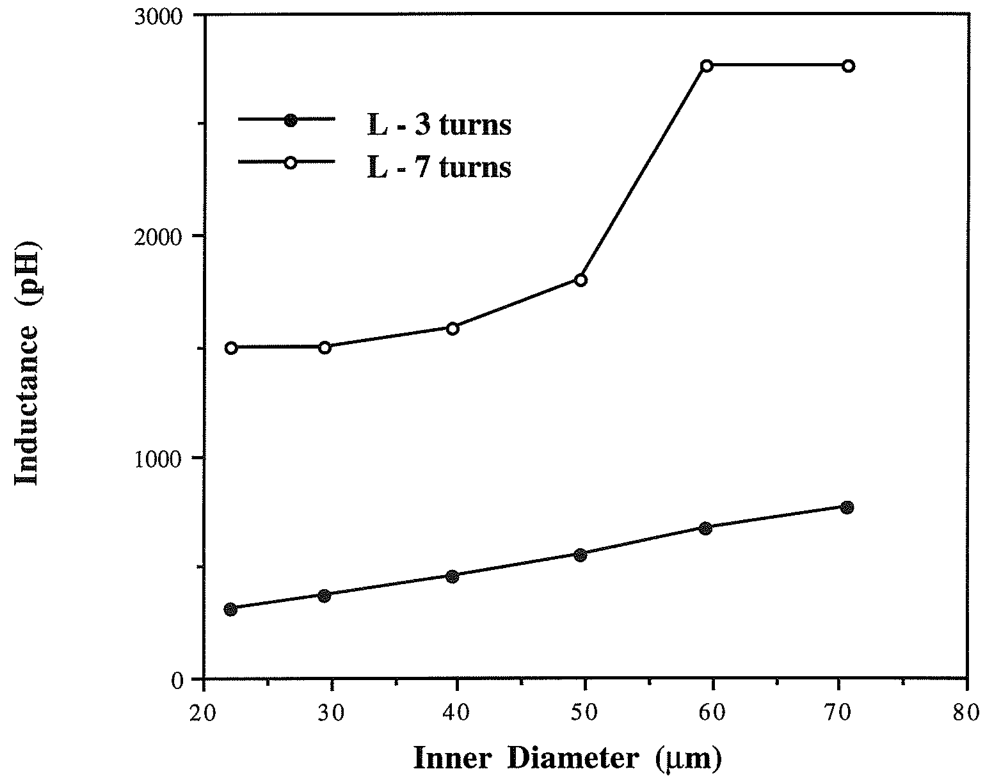

Fig. 20 Inductance vs. Inner Diameter for One-Port Microcoils

Table 4 Model Data for Varying Line Width: Two-Port

No. Turns	*Line Width (μm)*	*Diameter Inner (μm)*	*Geometry*	*lead L (pH)*	*paras C (fF)*	*main L (pH)*	*main R (Ω)*	*main C (fF)*
3	3	50.0	D	0.45	4.4	1000	34.5	1.90
3	4	49.5	D	1.30	5.6	1020	28.5	0.71
3	5	50.5	D	0.93	6.9	1070	26.8	0.38
7	3	50.0	D	240.0	10.0	4390	98.7	8.7
7	4	49.5	D	170.0	13.0	4870	86.0	8.4
7	5	50.5	D	110.0	17.0	5490	83.2	8.0

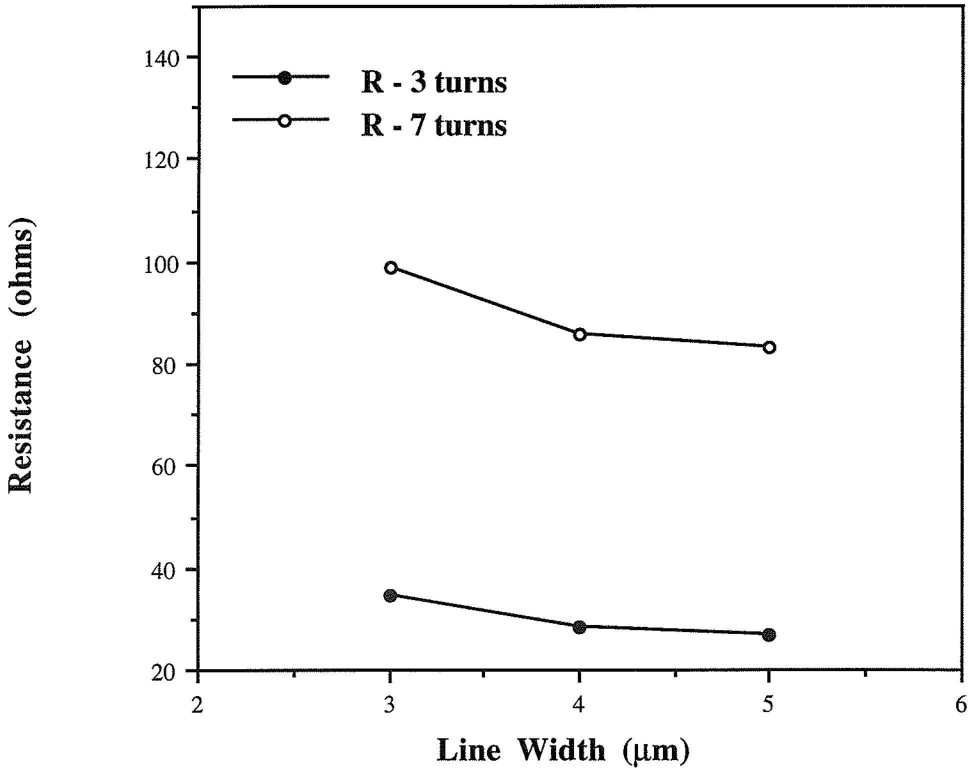

Fig. 21 Resistance vs. Line Width for Two-Port Microcoils

Table 5 Model Data for Varying Line Width: One-Port

No. Turns	Line Width (μm)	Diameter Inner (μm)	Geometry	lead L (pH)	paras C (fF)	main L (pH)	main R (Ω)	main C (fF)
3	3	70.0	A	0.00	21	782	25.3	0.10
3	4	70.5	A	0.00	24	776	20.8	0.10
3	5	70.5	A	0.00	26	782	18.9	0.01
7	3	70.0	A	480	39	2730	58.3	39.0
7	4	70.5	A	570	43	2760	55.7	45.0
7	5	70.5	A	600	47	2870	52.8	49.0

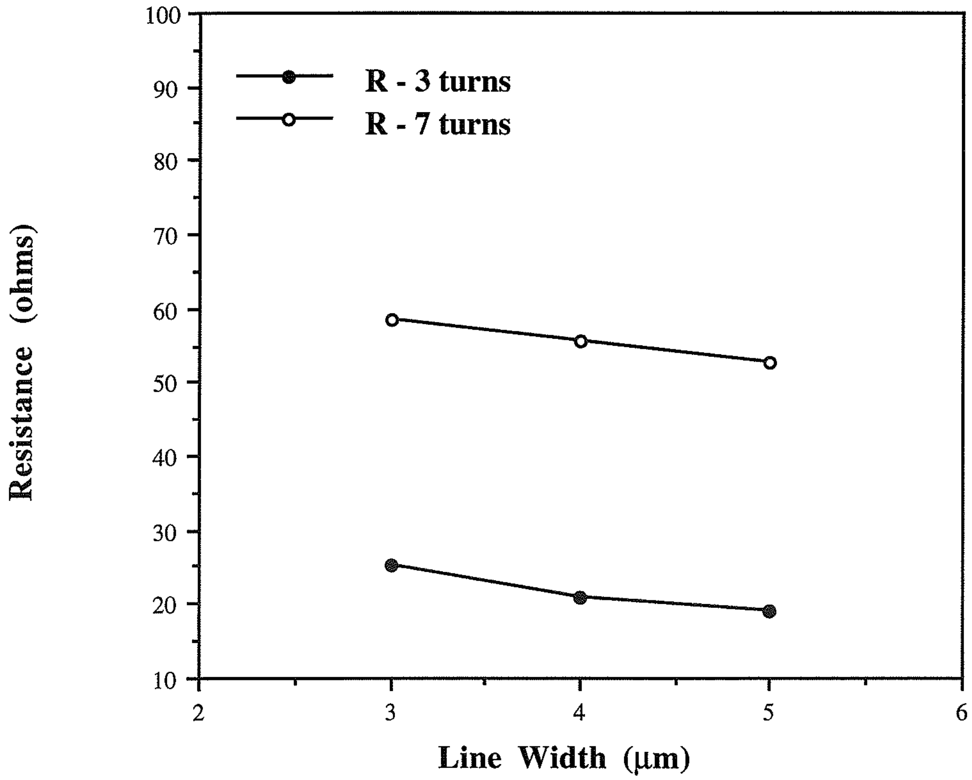

Fig. 22 Resistance vs. Line Width for One-Port Microcoils

4. DISCUSSION

The flowchart in the methods section (Fig. 2) illustrates the steps needed in the creation of a device. Considerations taken into account when creating a design implementation are strongly affected by processing considerations. These considerations include: limitations of equipment, repeatability of process conditions, and time required for a particular processing step. For example, there are limitations placed on the design implementation by the electron beam (e-beam) system used to write the mask (also see Appendix B for further information concerning mask creation). The concept microcoil would have a spiral configuration with the spacing between the lines equal to the width of the conductor. However, due to the writing configuration of the e-beam system, modifications had to be made in the design implementation. In particular, since the system moves the beam according to an equal grid spacing, an arc would be written as a series of steps. To overcome this, the first design implementation, on the PECK and MASK2 masks, used a square-shaped coil with 90^o corners. After MASK2 was created and the process steps completed, it became clear that there would be great difficulty in reproducing sharp corners during processing.

To overcome the difficulty in reproducing sharp corners, a mitered-edge coil was used as the second design implementation on NEWGEOM. The edges must be at 45^o so that the e-beam system can continue writing on the equal grid spacing. It was also discovered after the generation I coil was implemented that redesign of the contact pad location would be necessary for complete testing on the values of resistance (R), inductance (L), and capacitance (C) (see Fig. 1). This new configuration was incorporated with the redesign of the coil turns. The NEWGEOM mask was used for the final results for this thesis. Through the iteration steps in the flow chart (Fig. 2), implementation of the concept design was close to, but not exactly in its originally intended form. The feature sizes for the coil turns remained at 1 to 5 μm for the generation I coil, but were 2 to 5 μm for the second generation. This was due to a LASI limitation which will subsequently be taken into account in any further design implementations. The contact pads were reduced from

75 μm in the first generation to 50 μm in the generation II coils This reduction in size was necessary for spacing. For the second-generation contact pad redesign, it was not known which of two possible design layouts would be better. Subsequently, both layouts were implemented on the most recent mask plate. The coil dimensions were repeated for each of the two layouts to allow direct comparison of the two designs. One of the layouts allows a two-port measurement (see Figs. 13 and 14) and one allows a one-port measurement (see Fig. 12). The two-port layout contains two ground planes which are located above and below the coil with a width of 50 μm, the length of which is modified for each coil so that the contact pads are in line to form a three-point measurement site.

Different substrates have different reflection coefficients from the surface interface. However, unlike in the semiconductor material, in glass substrates internal reflection occurs during lithographic processing (see Fig. 23). The PR used in this process, AZ5214, was designed for use at 365 nm. However, the Karl Suss Aligner's UV source is 320 nm. At an exposure wavelength of 320 nm, where the PR was spun directly onto the glass surface, a phenomenon called buckling occurred. During development, PR would lift from the surface in areas where it should not have developed, i.e., due to reflection, the PR/glass interface received a large enough dose of UV to change the solubility of the PR. It is theorized that the excessive reflections from the PR/substrate interface and from the substrate/chuck interface were exposing areas in the PR other than those desired. To reduce this effect, a black nonreflective backing was placed between the metal chuck and the substrate. This eliminated most, but not all of the buckling problem. To further reduce/eliminate the problem, a silicon nitride coating 2000 Å thick was deposited onto the clean glass substrate surface. The buckling problem was completely eliminated, because the nitride coating is very absorbing at 320 nm. Silicon nitride has an absorption coefficient of approximately 30000 cm^{-1} at 320 nm.[19] This nitride coating reduced the PR interface reflection coefficient, thus requiring an increased dose of UV to expose the lower areas of the PR, since UV light does not have 100% transmission through the PR. A dose larger than the threshold will not change the solubility significantly, but will change the required development time. The substrate is coated on both sides with nitride for ease in processing.

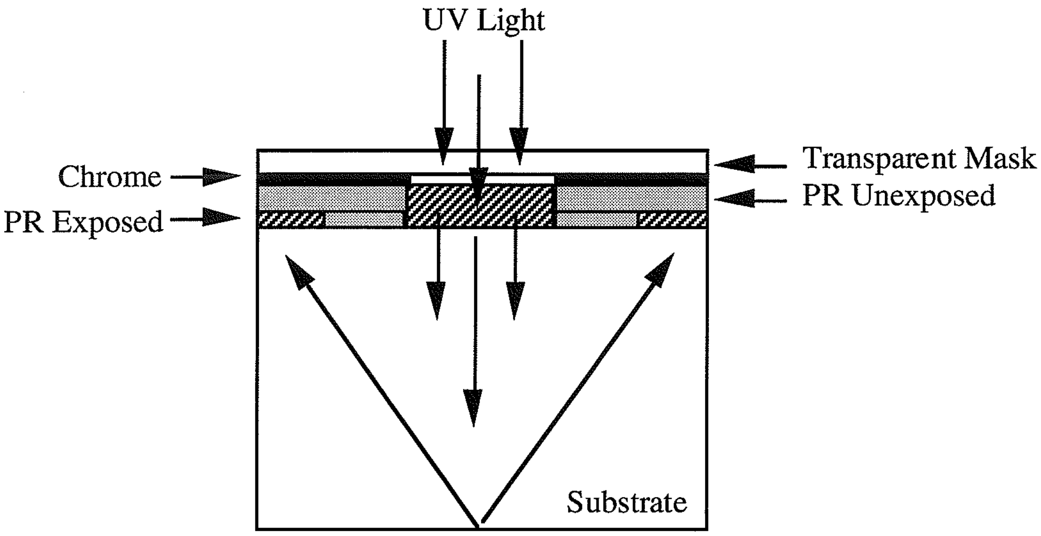

Fig. 23 Illustration of Buckling Phenomenon

During the development of the fabrication process, it became clear that the chemical reactivity of certain substances affected the processing method. For example, lift-off is used in this process so that no etch is necessary. In general, etching one metal is easier than etching two metals. For this application, a low resistance metal is desired, thus Au is chosen over Al. However, it is necessary for good Au bonding to have a metal/metal bond since Au will not bond well with many materials. Thus, unless an etch was capable of etching Ti as well as Au, two etch solutions would be necessary. There is a standard Au etch (Type TFA - Transene Co.) which can be used to etch the Au; however, a typical Ti etch is hydrofluoric acid (HF). The problem is that HF also etches the glass substrate; HF is typically used to etch silicon dioxide. Thus, not only are there more steps required, as well as the use of caustic chemicals, but this etching process will also remove substrate material. During the course of the process development, etching of Ti with 9:1 DI:HF was used. In a 2 sec etch, 200 Å of Ti were removed, but in that same time, 1.35 μm of the glass substrate were also etched.

Currently the substrates are soda-lime mask glass (Hoya) cut into 1" squares. Originally, microscope slides cut into 1" squares were used, but the surface variation of the microscope slides was too large. The surface variation was evident during development. It is important during any optical lithography step that the PR be of a uniform thickness to ensure an equal UV dose across the substrate. In general, there are steps on the surface and if these steps become too large, it is necessary to planarize the surface prior to spinning on the PR. It is in this way that it became apparent that the microscope slides had too much surface variation to allow an equal dose across the substrate. This type of effect can be seen during development, where the uneven exposure dose would create the necessity of uneven development times.

5. FUTURE WORK

In NMR applications, the lower the resistance, the lower the V_{noise} in Eq. (1). Deposition of metal with lift-off is limited by the thickness of the PR, i.e., as mentioned previously, the PR should be thicker than the deposited metal. Etching is also difficult. Monetary limitations are imposed during evaporation since the Au will coat every surface it comes in contact with inside the evaporator. An extremely large amount of Au would be necessary to evaporate, for example, 2 μm of Au. Currently, to evaporate 0.22 μm, 1 and 1/2 slugs of Au are used. Evaporation of 2 μm would require approximately 13.6 slugs of Au. Even if it were feasible to evaporate this much Au, it would need to be etched into the desired pattern. Wet etching (acids) is not feasible as mentioned earlier; dry etching (gases) may be possible, but would add to the complexity of the process. As an alternative, plating can be used to create thick layers of conductor. The general instructions are given below along with Fig. 24 for illustration.

1) Deposit 50 Å of Ti and 200 Å of Au onto the surface of the substrate with the evaporator .

2) Spin on and pattern PR, opening windows in areas where metal deposition is desired.

3) Plate in plating solution.

4) Remove PR with acetone.

5) Argon mill the original evaporation of Ti/Au.

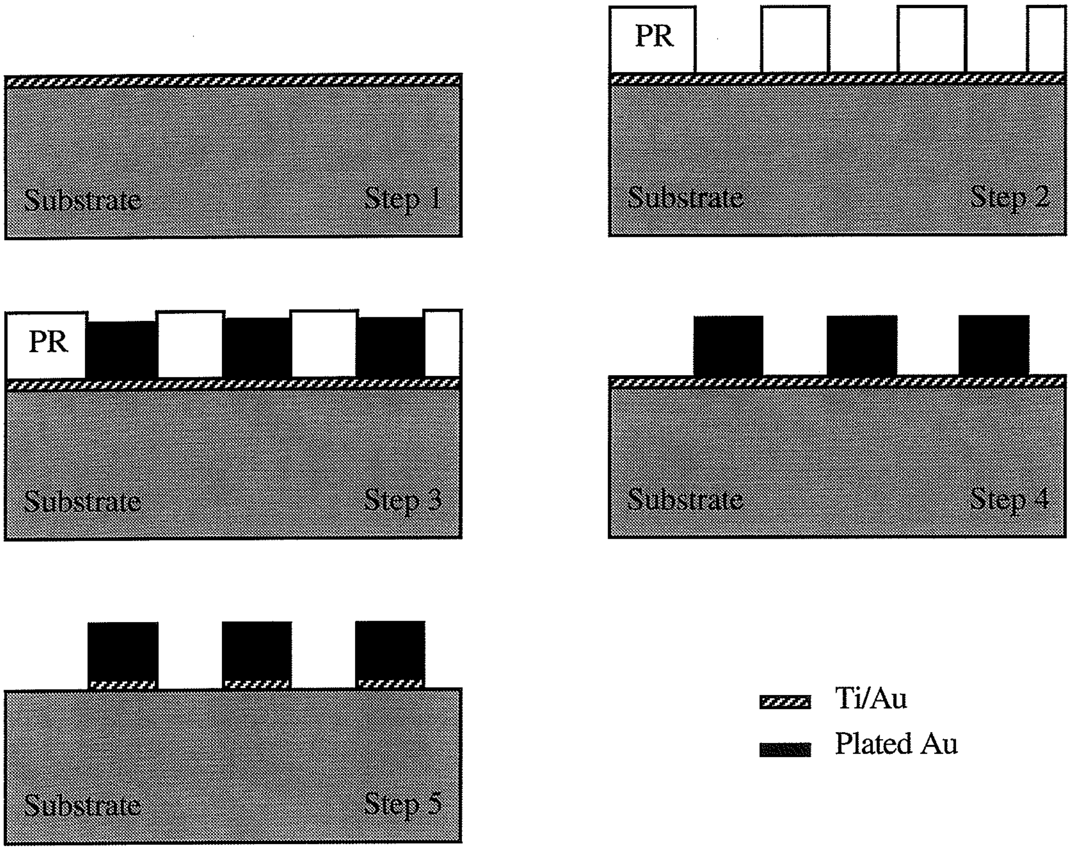

Fig. 24 Au Plating

APPENDIX A
OVERVIEW OF THE FABRICATION PROCESS

Microcoils are fabricated using techniques similar to those used in the microelectronics industry. These techniques involve many separate processes and a number of specialized pieces of equipment. In this and the following appendices the individual steps taken to fabricate NMR microcoils on glass substrates are described in detail. This appendix provides an overview of the processing techniques and some of the issues involved in choosing a particular process. Also described in this appendix are some of the techniques that were attempted and discarded, as well as some reasons why these techniques did not work for this specific application. Appendix B describes the mask making process. Appendices C, D, E, and F contain detailed instructions pertaining to the use of the equipment needed to process the NMR microcoils. Terminology which may be unfamiliar is defined in Appendix G. Training is required before using equipment located at The Microelectronics Laboratory (ML), the material appearing in the appendices should be read prior to training. It is also recommended that new students attend a laboratory chemical handling safety class. Appendix H contains the specific processing information for those coils used to collect data. Finally, Appendix I contains information pertaining to the testing of the coils for use in fitting the model. The diagrams shown in this appendix are intended to help illustrate some of the fundamental ideas used in the processing techniques. In addition, there are several good books which illustrate these ideas more completely, such as Anner,[20] Williams,[15] and Wolf and Tauber.[11]

The microelectronics facility contains cleanrooms. The use of the cleanrooms is necessary for repeatability in designs with small features, such as the microcoils. In the cleanroom, researchers are required to wear special clothing over their street clothes: a coverall, cap, and booties. This special clothing reduces the threat of contamination to the substrate from human bodies, e.g., from hair. The average diameter of a human hair is 80 μm, while a typical feature line width in microelectronic designs is 5 μm. Thus, a single human hair could short out a microelectronic device. Cleanroom facilities are classified according to the concentration of airborne particles of size 0.5 μm and larger per cubic foot. This is called the class of the cleanroom. The Microelectronics Laboratory has two different classes of rooms inside the cleanroom area. The processing area, which is used for pattern transfer, has ultraviolet (UV) filtered light and is class 100. The other group of rooms is class 1000 and has crystal growing areas, dry etching equipment, and preparation areas. The class 1000 cleanrooms have normal white lighting, i.e., no UV filtering.

Some of the machines used in the fabrication of microcoils are: the plasma enhanced chemical vapor deposition (PECVD) system, the Karl Suss aligner, the Planar Plasma Reactor, and the Cooke Vacuum Products (CVP) evaporator. The PECVD system is used to deposit insulating material onto the substrate. The Karl Suss aligner is used to transfer a desired pattern onto the substrate. The Planar Plasma Reactor creates an oxygen plasma which can be used to clean the substrate. The CVP evaporator is used to deposit metals onto the substrate. The instructions for these pieces of equipment are found in the remaining appendix material. For the key pieces of equipment, a few important issues necessary for the process overview will be described in this appendix. These pieces of equipment will be referenced throughout this overview.

The PECVD system is used in this process to deposit silicon dioxide and silicon nitride on the substrate. Silicon dioxide or nitride grown via PECVD differs significantly from thermally grown oxide or nitride. Thermally grown oxide or nitride require silicon from the substrate to be used as the source. The PECVD system does not use any of the substrate to create the insulators; it simply deposits them over the existing material. The PECVD system uses source gases to create a plasma above the substrate. Inside the plasma a reaction takes place in which the by-products are the desired insulator substance, which are inactive and subsequently drop down out of the plasma onto the substrate, i.e., are deposited on the surface. The other products of the reaction are highly volatile and are removed from the chamber with the vacuum pump system. Some instructions are growth data are located at the PECVD system. Further instructional information is available in Appendix E.

The Karl Suss aligner houses an ultraviolet source (UV) which is used to alter the chemical properties of a photosensitive material called photoresist (PR). The aligner is also used to spatially move a substrate to the correct location underneath a quartz (or soda-lime glass) plate which has patterns to be transferred to the substrate. The plate is called a mask which has a pattern formed from dark and light areas. The dark areas, chrome for this process, are opaque to UV while the light areas are free of this opaque material and are transparent to UV light. Quartz and glass are transparent to UV; however, quartz has better transmitting abilities than the soda-lime glass, thus when using a quartz mask, shorter exposure times are required. Quartz is used more often for the mask plates. Aligner instructions are available in Appendix D.

The CVP evaporator is used to deposit metals to a substrate. The substrate is placed with the processing side of the substrate facing toward the source metal. Depending on the melting point of the metals or the form of the source material, the metal may be melted with an electron beam (e-beam) or thermally by generating a current. The e-beam creates excess radiant heat and should be used only if the higher temperatures are necessary to melt the metal. Instructions for the CVP evaporator are available in Appendix C. For completeness, it should be mentioned that there is another machine available at the ML for the transfer of metals, the sputtering machine. Sputtering operates on a different principle from the CVP evaporator. Sputtering requires the generation of a plasma. The atoms in the gas plasma (typically Ar) are ionized and accelerated towards the target. Target material atoms are then knocked off, and in turn will move to the substrate and form bonds with the surface the molecules encounter. This piece of equipment is used to obtain good step coverage, whereas the CVP evaporator is used to obtain coverage only in areas within the line-of-sight of the source.

Each fabrication technique can be used to produce images on many different substrates: semiconductor materials such as Si, GaAs, and InP as well as other materials such as ceramics, glass, and quartz. Semiconductor material is an obvious choice when creating integrated circuits, which require electrical conduction between devices. However, MRI requires a nonferromagnetic and nonconductive substrate. A number of different metals may be used such as aluminum, titanium, gold, nickel, and copper. Some of these metals are used alone; however, combinations of metals can be used to produce desirable effects. For example, to obtain better bonding characteristics, titanium is deposited on a surface prior to gold. Many different materials such as silicon dioxide, silicon nitrides, and polyimides can be used as insulators, both electrical and thermal. Other considerations for material usage come from the eventual application of the design, such as, in this case, the use of NMR microcoils in biological research in which conductive water-filled samples are used. Some characteristics which affect the choice of substrate material as well as the fabrication method are conductivity (see Table A.1), reflectivity, and chemical reactivity. For example, the reflectivity of GaAs at 320 nm is approximately 30%, but the reflectivity of any substrate can be changed through anti-reflective and reflective films. Chemical reactivity affects such things as the selectivity of etchants.

Table A.1 Electrical and Thermal Conductivity

Material at 300K	Thermal Conductivity	Electrical Conductivity
Si- intrinsic	1.5 W/(cm ^{o}C),	1/(2.5e+5 Ω-cm)
GaAs - intrinsic	0.45 W/(cm ^{o}C)	1/(4e+8 Ω-cm)
glass (soda lime)	1.5 W/(cm ^{o}C)	

Design intent/mask making: a flowchart illustrating the steps in the fabrication of a monolithic device is shown in Fig. A.1. The initial stages of design are strongly influenced by processing considerations. These considerations include: limitations of equipment, repeatability of process conditions, and time required for a particular processing step. For example, there are constraints

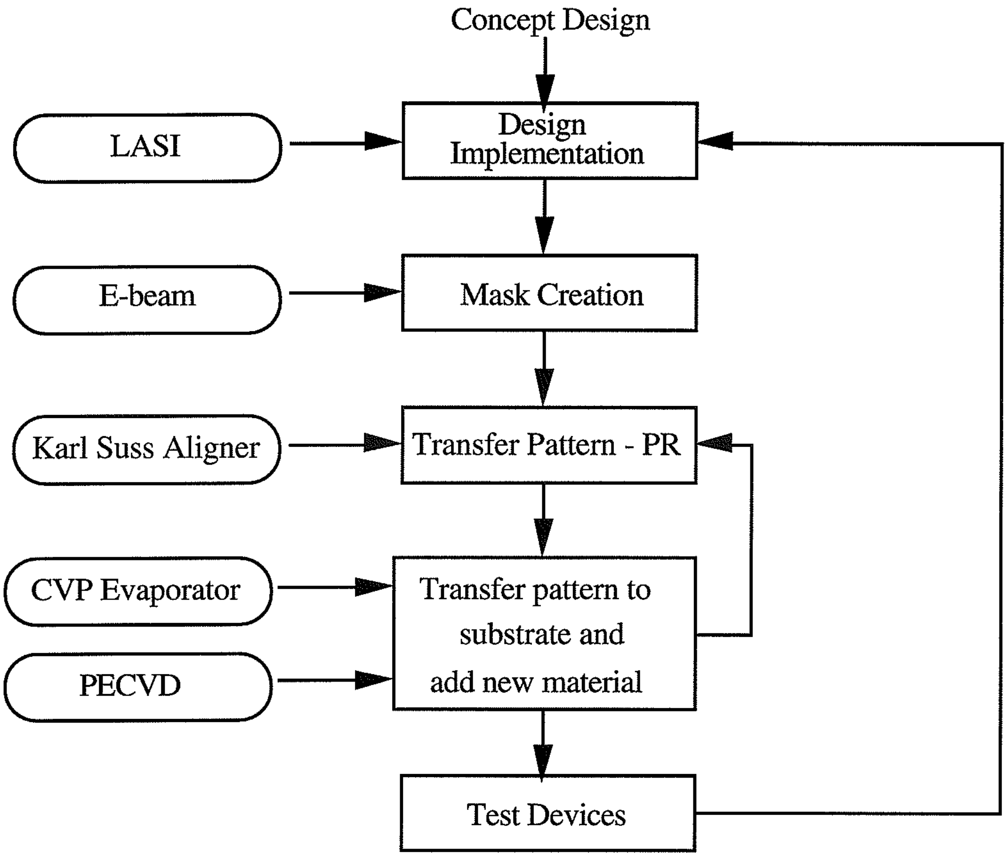

Fig. A.1 Process Flow Diagram

placed on the design by the electron beam (e-beam) system used to write the mask. The system moves the beam according to a grid spacing. Although the grid spacing can be manipulated somewhat, inevitably an arc would be written as a series of steps. One possible solution to this problem is to use a square shape, with 90^o corners. Our first generation coil has these 90^o corners and is shown in Fig. A.2. Due to the difficulty in reproducing sharp corners during processing, an octagon-shaped coil was created. This generation II coil has corners drawn as 45^o angles and is also shown in Fig. A.2. Since the e-beam moves along a grid spacing, 45^o angles are possible by moving corner-to-corner across the grid, without the series of steps needed for any other angle. For the type of coils shown in Fig. A.2, the feature sizes range from 1 to 5 μm for the coil turns and 75 μm for the contact pads and ground planes. The intended design is drawn with computer-aided design (CAD) program, such as the PC-based Layout System for Individuals (LASI) written by Dr. David Boyce. The mask is created when the design is written onto a mask plate using the e-beam. This process is described in more detail in Appendix B. Once the mask plate has been created, the pattern can be transferred onto a substrate. This may require several repeated processing steps if there is more than one layer in the design. After the processing has been completed, the devices can be tested. Knowledge gained from the processing cycle can subsequently be used to further modify the intended design.

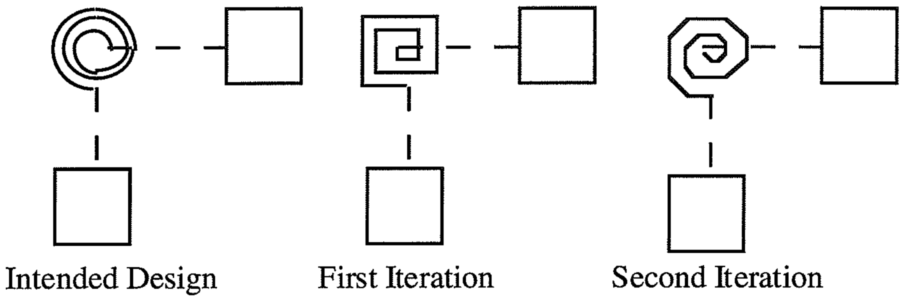

Fig. A.2 Coil Evolution

Processing information: once a pattern has been created, the photoresist (PR) is used as a medium of transfer. In optical lithography, UV light is used to alter the chemical properties of the PR and imprint the pattern into a thin film which has been spun onto the substrate. After the thin film has been altered, some of the PR will be removed in a step called development. Development requires different solubility between exposed and unexposed areas of the PR to selectively remove the PR. After development, the pattern can be transferred to the substrate. Repeated steps with different masks allow the transfer of complicated patterns. Occasionally, extra material will be deposited onto the substrate between these steps, often to act as an insulator.

There are two basic types of PR, positive and negative. The development of exposed positive PR opens windows in the PR, while it is the development of unexposed negative PR which opens windows (see Fig. A.3). The mechanisms involved in exposure are different in the two types of PR. Positive PR is composed of a base resin, a photoactive component and an organic solvent, and is developed with water-based inorganic developers. Both the unexposed and exposed regions develop, but at very different rates. Positive PR is less sensitive to UV and requires longer exposure times than negative PR. Negative PR is composed of organic polymers and is developed with solvents. When exposed to UV light, negative PR crosslinks. The exposed region does not develop; it does however, absorb the developer which dramatically reduces the transfer integrity of small features. In general practice, when using negative PR, features must be larger than 2 µm.

Prior to spinning on PR, all substrates should be cleaned to remove any particulate from scribing and surface contaminants, such as sodium. Cleaning is done with a trichloroethane (TCA) soak, acetone rinse, isopropyl alcohol (IPA) rinse, de-ionized water (DI) rinse to remove TCA residue, IPA rinse, and N_2 dry. All of these chemicals are located in the solvent hoods in ML. Gloves must be worn when working with these chemicals.

After cleaning, a bakeout is done to remove moisture from the substrate. Thicker substrates require a longer bakeout time to compensate for the heating gradient. The processing characteristics of AZ5214 (Hoechst Celanese Corporation), the positive PR with imaging reversal capability used in this process, are extremely sensitive to the moisture content of both the solvent portion of AZ5214 and the room humidity. Note that if the PR is coming from the refrigerator, it must be warmed for at least one hour before being opened, otherwise water will condense inside the storage container. A pipette is used to place the PR onto the substrate prior to spinning. Blow N_2 through the pipette before placing the bulb on the end; this will remove any particulate inside the pipette and prevent contamination of the PR. Do not let any PR get into the bulb, since this could contaminate the PR in the future. Place the substrate on the proper chuck in the spinner hood. Pick a chuck whose raised area is approximately the same size as the substrate. When spinning, a vacuum is pulled to keep the substrate in place; if the chuck is larger than the sample, PR will be pulled into the vacuum system. The spinner is started with a foot switch. The system will pull a vacuum only when a substrate is on top of the chuck, and the chuck will spin only if the

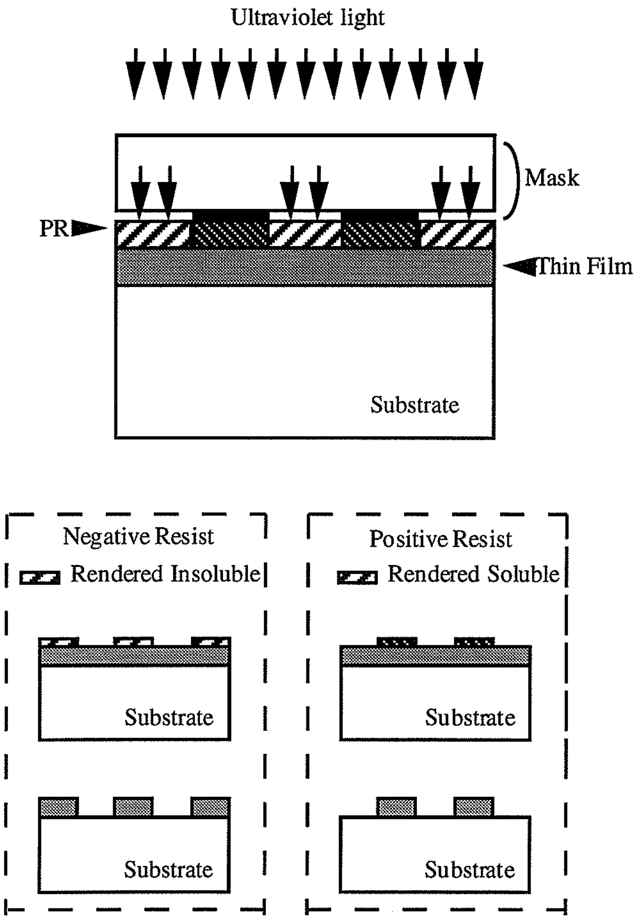

Fig. A.3 Ideal Exposure and Development of Positive and Negative PR

system is pulling a vacuum. Start spinning. While the chuck is spinning, blow off any particulate that may be on the substrate with N_2. The time and speed of spin determine the final thickness of the PR layer. This process spins at 4500 rpm for 30 sec, which results in a 1.2 μm layer of AZ5214. Stop the spinning by pressing the other button on the foot switch. While stopped, cover the entire surface of the substrate with PR. Once the surface is covered with PR, start spinning again. Once the spinning has stopped, pick up the substrate carefully and softbake at 110°C for 90 sec. The spinning drives out some of the carrier liquid, but the surface is very vulnerable until it has been softbaked. The softbake hardens the surface and drives off more moisture. Once the substrate has cooled it is ready for exposure.

Exposure can be done on the Karl Suss and occasionally on the flood exposure machine. The wavelength of the Karl Suss is 320 nm and the wavelength of the flood exposure machine is 365 nm. The PR, AZ5214, was designed to be used at 365 nm; the processing characteristics change when it is used at a different exposure wavelength. Adjustments in UV dose must be made when using different wavelength sources. Operating procedures for the Karl Suss are located at the machine in ML. Additional information and instructions appear in Appendix C. Pattern transfer into the PR can be done with one exposure, as illustrated in Fig. A.3, using either positive or negative PR. There is also another way to transfer a pattern. It is used to acquire a negative image with positive PR; it is called image reversal and involves two exposures. The first exposure changes the solubility of the exposed regions; however, a reversal bake is then done to change the solubility of that area again, making it totally insoluble in the developer, similar to the exposed regions of negative PR. The second exposure changes the solubility of the remaining PR making it more soluble in the developer. The reversal bake is especially sensitive to temperature. The time of the reversal bake should be sufficient to heat the substrate and change the initially exposed regions to insoluble.

The development of the PR can be done with a number of different solutions. The choice of developer affects the development time, which also depends on the dose the PR has received. The developer, MF327 (Shipley) is used in this process, but others such as MF319 (Shipley) can also be used to develop AZ5214. The developer should be constantly agitated during development. Typical development times are on the order of 45 to 90 sec. A regular routine for this agitation should be used every time to reduce variability in development times. The agitation is necessary to remove used developer from development sites and replace it with fresh developer. If the sample is not agitated, smaller sections may not be developed, increasing development time. Development continues until the sample is rinsed with DI, even after it has been removed from the developer solution. Proper development times are necessary, since an interrupted development may leave partially developed PR that subsequent development will not be able to remove.[21]

In the current process, the substrate is patterned using the image reversal technique. Lift-off is used to deposit the thin film pattern directly onto the substrate, instead of etching the pattern into the thin film. Note that the thin film in Fig. A.4 could be any material, for example, semiconductor (Si), insulator (glass), or conductor (Ti/Au). Figure A.4 illustrates both the etching and the lift-off steps. A brief summary of the process steps used to etch a pattern into a PR-coated thin film is provided below: first, PR is spun onto the deposited thin film, then the PR is exposed with UV light through a mask and developed. Once the pattern has been transferred to the PR, it is used as a mask for selective etching into the thin film. The pattern is thus transferred to the substrate. The PR must prevent etching of the material under the PR. Lift-off is used to deposit a pattern directly onto a substrate. The PR is spun on prior to the desired thin film. For this process, lift-off was used to pattern the metal. The process has a metal combination of Ti/Au. The PR is patterned with the profile shown in Fig. A.4. Metal is deposited after the PR has been developed. The excess metal is removed with heated acetone which dissolves the PR. The patterned metal (or any other thin film) is left on the surface of the substrate. No acids are used in this process. Thin films are required to be thinner than the PR. This, as well as the profile, ensures that no physical connection occurs between the thin film on top of the PR and the thin film on the substrate.[15] Instructions for the metal deposition process are listed in Appendix C. To remove the unwanted metal, it is necessary to soak the substrate in a heated acetone bath. This process should take about 10 min. If the PR/metal has not lifted from the substrate after 15 min of heated acetone bath, the substrate, inside a plastic container (glass might break) filled with acetone, is placed in the ultrasound machine for 5 sec. In general, however, if the PR has the correct lift-off profile, this extra step should not be necessary.

As mentioned previously, these lithography steps are repeated as necessary to complete a device. In this process there are three mask layers (see Fig. 3 in body of thesis). The first contains the coil turns, the second contains via holes for electrical conduction, and the third contains the contact pads. The first and third mask levels are patterned with the lift-off process. The second layer

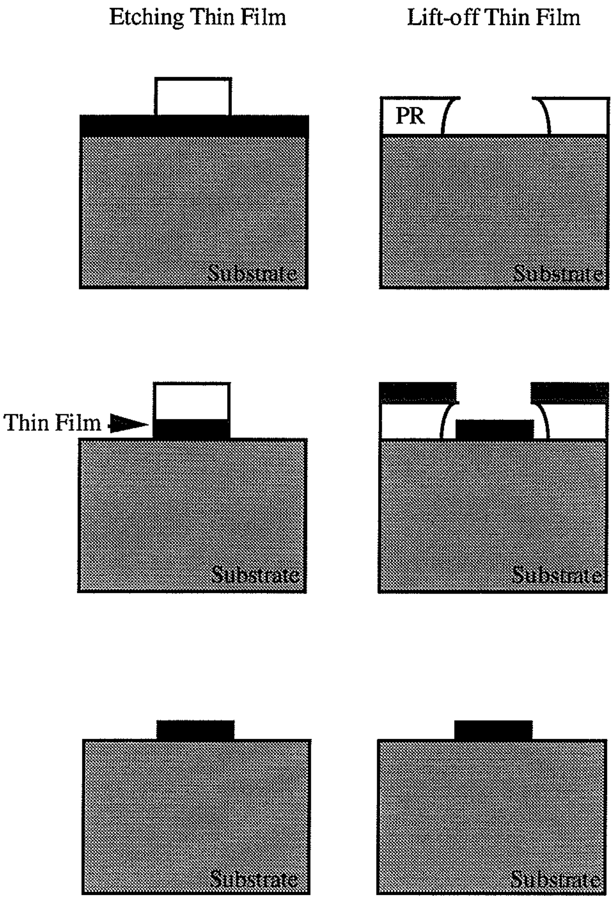

Fig. A.4 Etching vs. Lift-off for Metal Patterning

requires the deposition of an electrically insulating layer, in this case silicon dioxide, and the etching of via holes through this insulating layer. The PECVD system is used to deposit silicon dioxide. For the PECVD system in ML, it is easier to control the growth characteristics of silicon dioxide than those of silicon nitride. The insulator is deposited 2800 Å thick to ensure a thick enough layer to avoid oxide breakdown at the corners over the coils turns which are 2400 Å thick. The oxide will deposit on corners at a 45° angle. After the insulating layer has been deposited, PR is spun onto the surface and the via holes are patterned into the PR. For this process a lightfield mask is used, thus, the via holes are also exposed using image reversal. It may be possible to use the original mask to pattern the via holes and the image reversed copy for the lift-off steps. Caution must be used, however, because some of the features on the mask become reversed during the image reversal copying procedure. More work needs to be done in this area.

It is a good idea to do a plasma descum before etching the oxide to insure that the via hole has been opened in the PR completely. A plasma descum is the process in which an oxygen plasma is used to remove organic material. At any point in the processing or mask copying if there is any chance that there is some PR scum left on the substrate, which is a residue left over after development, a descum can be done in either the reactive ion etch (RIE) or Planar Plasma reactor. Directions for the Planar Plasma reactor are located at the machine. The RIE system is more complicated to use and requires more training, but is capable of supporting more dry processes than the Planar Plasma reactor. The oxide must be etched after the PR has been patterned. The index of refraction for silicon dioxide is very close to the index of refraction for the glass substrate, making it is very difficult to see processing done on this layer. We use buffered oxide etch, which is buffered hydrofluoric acid. For the substrates, numbered 010494A - 010494D, whose processing steps are listed in Appendix H, the oxide etch was stopped when the area around the developed hole in the PR, i.e., the area under the PR, changed color. As with any substance, this is an indication that the thickness has changed. Different etch solutions can be used. However, note that substances which etch silicon dioxide also etch the glass substrate. Caution must be used with any etching solution in this regard. For example, a 9:1 DI:HF etch, which etches titanium, will etch 1.35 μm of glass in 2 sec.

The final processing step after the second lift-off is an alloy which strengthens the contact pads. The alloy chamber is heated to 480°C and the substrate is inserted for 1 min. This time is sufficient for the Au to flow. This flow could be as much as 0.5 μm on each side of a line. Usually, an alloy processing step is used when ohmic metals, that is, a Au/Ge alloy, Ni and Au, are deposited instead of Ti/Au.

Alternate processing: initial attempts at making the microcoils were made in the ECE 344 laboratory located in the basement of Everitt Laboratory. The aligner located there is a Kasper model similar to the one located in the ML. The coils were processed using aluminum instead of Ti/Au on the same glass substrates. Standard procedures exist for etching, evaporating, and exposure using the same positive PR, AZ5214. No procedure was documented for image reversal. The exposure times were linearly scaled for the intensity in the ECE 344 laboratory from the recommended image reversal exposure times used on the Karl Suss. This procedure worked well; however, it is theorized that the process has a wide latitude and that this is the reason why the scaling worked. The coils which were processed in the ECE 344 laboratory did not exhibit the buckling phenomenon in the thesis. Since the ECE 344 laboratory is a teaching facility, not all of the equipment necessary to complete the project was available and since there was less control over the environmental characteristics, the project was moved to ML.

The first processing techniques for lift-off used chlorobenzene to achieve the lift-off profile instead of image reversal. The chlorobenzene approach did not work with this process. It is unclear whether this was a problem with the substrate or with the PR. A good reference for information concerning chlorobenzene can be found in Williams.[15] The chlorobenzene technique was used in processing for the first generation of the coils processed in the ML cleanrooms. The process steps for these microcoils are listed in Appendix H. An alternative procedure for performing image reversal is shown below. It is intended to be used with the Kasper, located in ML. Note, however, that the intensity is not monitored as it is for the Karl Suss. One should therefore measure the intensity before using the procedure. This procedure was provided by Al Hanson, a Ph.D. student with Professor Stillman.

1) Spin on AZ5214 diluted 2:1 with propylene glycol monomethyl ether acetate (PGMEA) at 5700 rpm (thickness should be ~5000 Å).

2) Softbake at 110 °C for 5 min.

3) Expose on Kasper Range 1, Intensity 1 for 18.3 sec.

4) Reversal bake at115 °C for 45 sec.

5) Flood for 5 min on Range 1, Intensity 1.

6) Develop with MF352 for 60 sec.

APPENDIX B
MASK MAKING

The creation of a mask plate begins with a design concept. This concept is drawn on a computer-aided design (CAD) system and converted to a file format suitable for the electron beam (e-beam) writing system. Any number of CAD systems can be used. The main requirement is that the pattern files be convertible to the necessary e-beam format. Figure B.1 Mask File Conversion illustrates the necessary file conversions. A very common program to use is the PC-based Layout System for Individuals (LASI) by Dr. David Boyce. Copies of LASI are located in the Microelectronics Laboratory to facilitate the conversion process.

Once the file conversion process is completed, the desired pattern is written onto a mask plate with the e-beam lithography system. The mask plate, usually quartz, has chrome on one side as well as a resist coating which is sensitive to electrons, instead of ultraviolet wavelength photons. The resist is exposed whenever high-energy electrons come in contact with the resist. There is a minimum number of electrons which must come in contact with the resist to change it chemically, just as with the optical resist. If there are multiple layers, which is unlikely in a mask, as in optical processing, the pattern must be aligned to the previous layer. This is done with registration marks. However, in doing this registration, any area over which the electron beam has searched becomes exposed. Another important aspect of this system is a problem called proximity effect. Just as during optical processing the desired pattern is not transferred perfectly due to diffraction effects, the electrons are reflected and can interact with the electron resist in areas other than the intended area. If the pattern lines are too close together, there may be overlapping reflections and the line integrity may be lost. More information concerning electron beam writing is available in Wolf and Tauber.[11]

For this process, the drawings were done in The Beckman Institute on a PC, but there are also machines available in the Microelectronics Laboratory (ML) with the software. LASI is updated often, so it is advisable to obtain the latest copy before starting the drawing; see John Hughes at the ML for a copy. After your drawing is completed bring a 1.44 Mb disk with the following five files over to the electron beam room inside the cleanroom at the ML, (please see Appendix A for more information about the cleanroom): *.tlc (your drawing) and *.dbd (there are four files). If the drawings were done on an earlier version of LASI some extra conversions may be necessary before proceeding. Consult John Hughes about this process.

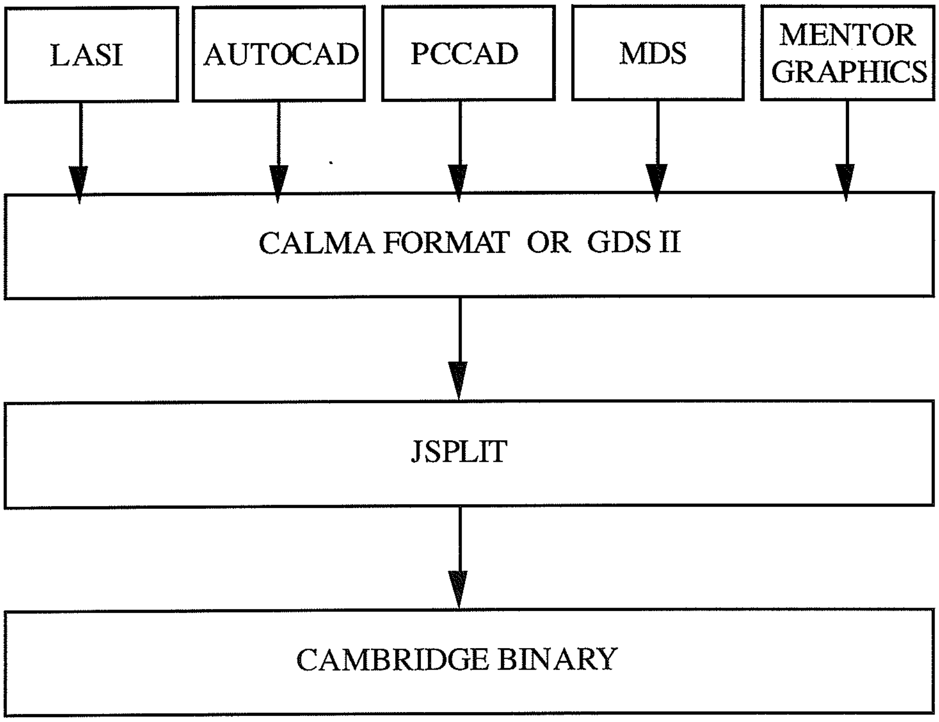

Fig. B.1 Mask File Conversion

The file conversion process is done at the ML and is illustrated in Fig. B.1 Mask File Conversion. The directions for doing the process follow the Fig. B.1; please press return after each command line. The command is on the left side. Further explanations are included on the right side under the description.

Command	Description
	Insert disk into PC.
cd lasi4	Changes to LASI directory.
mkdir "Peck"	Make your own subdirectory, one for each project.
cd "Peck"	Change to your directory.
copy a:*.dbd c:\lasi4\"Peck"	Copy all .dbd files to your personal directory; this allows you to run LASI with your own settings.

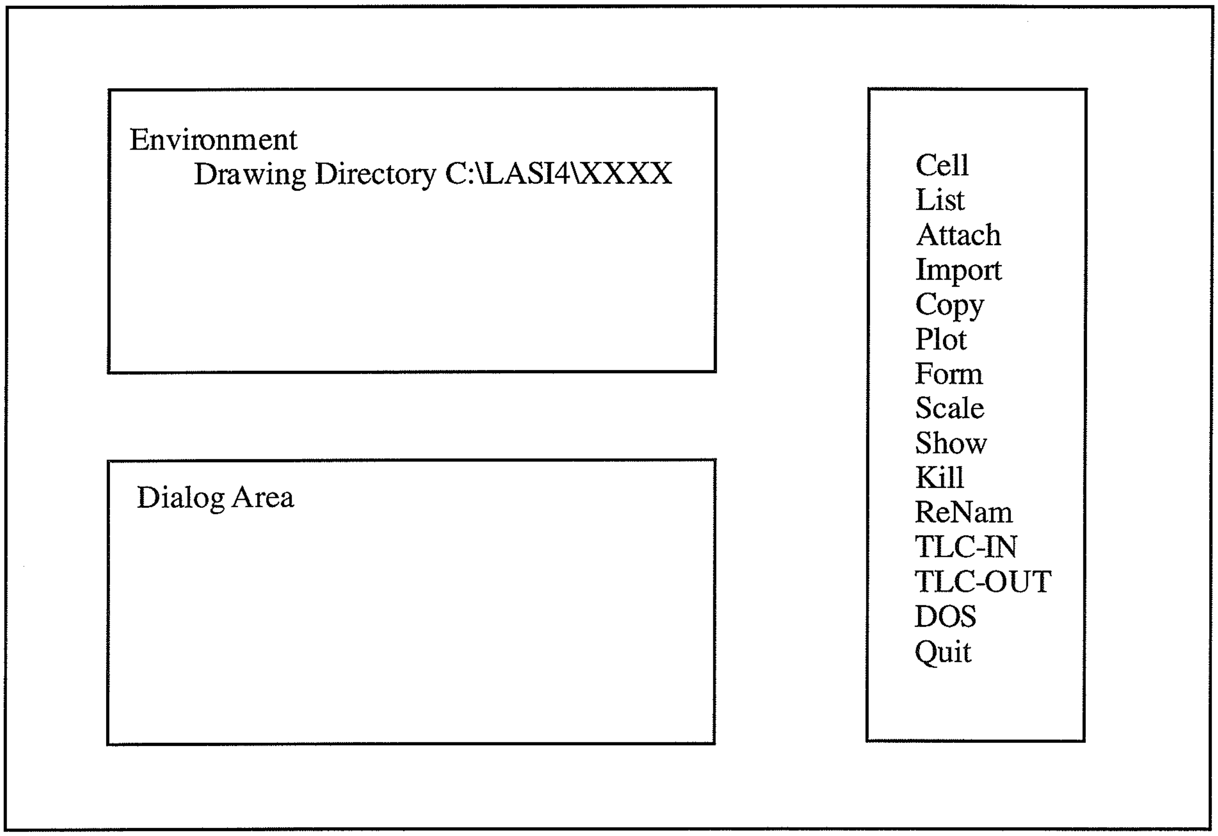

Fig. B.2 LASI Main Menu Screen

lasi	Starts LASI. You will see Fig B.2 on the screen.
TLC-IN	Select "TLC-IN" from menu; this will bring your file into LASI on this PC.
List	Move cursor with the mouse over the menu choice "List" and press right mouse button; this will show a list of the drawings in your directory, i.e., those files brought in with tlc-in. Move cursor with the mouse over your file and click the left mouse button to select. The next screen should be the current drawing. Check drawing.
select "sys"	Quit drawing and go to main menu.
Quit	Exit from LASI.
l-c	This will convert your LASI files to the CALMA stream format. Answer questions. This program also has a help screen.
telnet	This will telnet from the PC over to the VAX computer.
"WHEELER"	At prompt type your username.
"xxxxx"	At prompt type your password.
md [.coil]	Make your own directory.

cd [.coil]	Change to your directory. The commands "ls" and "dir" both work to see file list.
Alt-f	Press "Alt-F" this will call up the ftp program.
ty ba	This is "type backup." It sets the file format.
get "filename".csf	Transfer the CALMA stream file to VAX computer. It will ask, "To local file:" -- you can simply use the same name "filename".csf.
quit	To get out of ftp program.
jsplit	This calls up the JSPLIT conversion program.
"filename".csf	Type your filename at the prompt.
"cellname"	Type the cellname at the prompt. This will be the same as your "filename" if you used the same name when creating your .csf file.
1,2,3,4	Type the layers you wish to convert at the prompt. Separate the layer numbers with a comma.
	You can press enter to answer the questions with the default value for the next three prompts.

dir	Check that your files have been converted. There should be two files, a coarse file ("filename"L1C.BV0;1) and a fine file ("filenameL3F.BV0;1) for each layer that you ran JSPLIT on, where the layer is the number after the L. There will also be two *.log files and a *.stm file.
logout	Type logout and turn off monitor. Remove disk from PC. Go to DEC terminal. The file conversion is completed and now you must write your job file.
	Press button in upper-right corner "Connect to VS 3100" to get the login prompt for VAX.
"WHEELER"	Type your username.
"xxxxx"	Type your password.
cd [.coil]	Get back into your directory.
EVE "filename"	EVE is an editor. This is where you edit/create your job file. See job file example below.
logout	Type logout when finished.
	You have completed creating all of the necessary files. Now simply fill out a job request form and give to John Hughes at the ML to have your mask made.

Example of a job file:

```
;   NEWGEOM.JOB
;
@HTS3M
KEY 5
;
LOG LG:[200,233] NEWGEOM.LOG
LON
;
;
;  ***********  NEWGEOM.JOB ************
;
;  LUANA LAVALLE AND CHRIS LE GRAND
;   11/23/93
;
;  3 IN QUARTZ DARKFIELD MASK
;  3.2768 MM FIELD;    20KV
;  *************************************
LOF
;
CLK 1 ??
;
@FOC40
@SBC40
@CCC40
;
MAP REL 64.5 84.0
;
;
LON
;
;  BEGIN FINE EXPOSURES (40NA)
;
TIM
;
LOF
;
;
!   TEST PATTERN #1
MEX -25.4 25.4
% [200,233] NEWGEOML2F.BV0
;
!  TEST PATTERN #2
MEX 0 25.4
% [200,233] NEWGEOML3F.BV0
;
ONT
;
!  TEST PATTERN #3
MEX 0 0
% [200,233] NEWGEOML4F.BV0
;
@FCL
LON
;
;  END OF FINE EXPOSURES
;
```

Page 2 of a job file example

```
TIM
;
LOF
;
;
CLK 1 800E3
;
@FOC160
@SBC160
@CCC160
;
LON
;
; BEGIN COARSE EXPOSURES (160NA)
;
TIM
;
LOF
;
;
!   TEST PATTERN #1
MEX -25.4 25.4
VRU 2
% [200,233] NEWGEOML2C.BV3
;
!  TEST PATTERN #2
MEX 0 25.4
VRU 2
% [200,233] NEWGEOML3C.BV3
;
ONT
;
!  TEST PATTERN #3
MEX 0 0
VRU 2
% [200,233] NEWGEOML4C.BV3
;
;
@FCL
LON
;
;  END OF COARSE EXPOSURES
;
TIM
;
LOF
;
@UILOGO
;
!  NEWGEOM.JOB COMPLETE
```

APPENDIX C
EVAPORATION (CVP) INSTRUCTIONS

Note: Please consult instructions located at the Cooke Vacuum Products (CVP) evaporator, located in the cleanroom in the Microelectronics Laboratory (ML), especially for modifications in the instructions. You must be on the approved users' list to use the CVP evaporator. Please see Ray Zich for official training.

1) System should be in "Auto Cycle" mode, cyropump should be on and ready, the mechanical pump should be on, and the light for the water interlock should be on. Check the crystal lifetime by pressing and holding the "LIFE" button on the thickness monitors (see Fig. C.1). If the monitor reads less than 10% please notify the student in charge (or John Hughes or Ray Zich at the ML) of the CVP before proceeding.

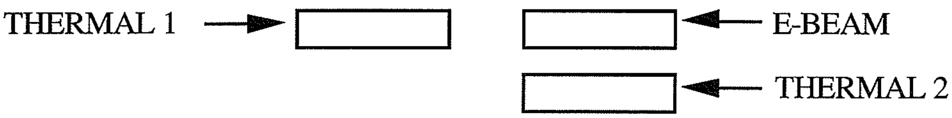

Fig. C.1 Thickness Monitor Locations

2) Press "STOP" (red button) before proceeding. This will close the hi-Vac valve, it should be open already.

3) Press "VENT" to vent the bell jar. "Vac switch" light turns off when done venting. If the light does not go off after a complete venting cycle press "VENT" again.

4) The bell jar is raised via the HOIST switch. Move it upward, "RAISE". Raise the bell jar only as high as needed to remove the sample holder.

5) Check the viewing port. Make sure the slides have been replaced.

6) Place your samples on the samples' holder.

7) Place the tungsten boat in the desired location, either thermal source #1 or #2 (see Fig. C.2).

8) Be certain to tighten the tungsten boat well for good electrial contact for melting.

9) Check to see that the large metal switch located on the bottom of the front panel below the bell jar indicates your desired location. Also, check to see that the required e-beam source is in the correct location.

10) Load the tungsten boat with desired metal (1 1/2 slugs of Au).

11) Lower the HOIST by moving it downward. The bell jar must come down only once to trigger the interlock. If the interlock does not engage, raise the jar 1 in and lower again.

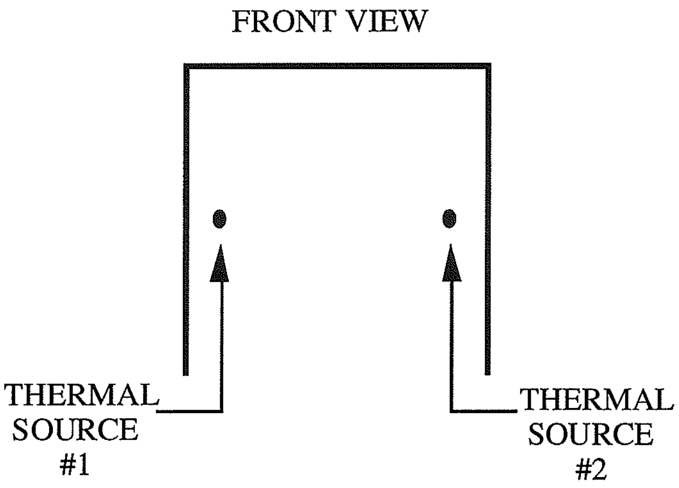

Fig. C.2 Front View of Bell Jar - CVP

12) Once the bell jar is lowered and the interlock has engaged, carefully slide the jar around, ~1/2 in to pick up vacuum grease.

13) Press "START" (green button). The system will rough down to ~100 μm before the roughing valve will close. After a few second delay the hi-vac should open. Check to see that the ion gauge meter is on 10^{-5} before proceeding.

14) When the hi-Vac opens, press "on" and then press the filament button to start the ion gauge. Immediately turn on the "degas." Turn the "degas" off after the pressure spike is gone.

15) Monitor the time from the opening of the hi-Vac to time of evaporation and write on logsheet.

16) Enter into the appropriate thickness monitors the information pertaining to your process.

17) To enter the data press "PROGRAM", then enter the density, Z factor, stopping thickness, and tooling factor, pressing "ENTER" after each entry. Do this for all the thickness monitors you will need.

18) Select the proper e-beam source (the list of source locations is on the front panel located at the top).

19) When the pressure is less than 8.0E-7, the machine is ready for evaporation. All four interlocks must be engaged to be able to perform an evaporation.

20) Return the range to 10^{-5} before proceeding so that the ion gauge will not trip off. If the ion gauge should turn off before/during evaporation, set the pressure range higher and press the red button again. Check that the emission adjust is zero on the e-beam panel.

21) To turn on the e-beam, turn on the power on the power supply, starting with the leftmost switch and move right (four switches). Press "RESET" on the high voltage panel and then on the source panel. Then press "START" on the high voltage panel and then on the source panel. Turn up the emission current until the beam is visible (~10 on emission dial). Center beam over source. Turn up the emission and leave for 2 min until melting occurs. Zero the thickness monitor and press "OPEN" on the thickness monitor to open the shutter and adjust rate to ~3 Å/sec with the emission dial. After the shutter automatically closes, return the emission dial to zero. Press "OFF" first on the source panel and then on the high voltage panel. Turn down the amplitude and frequency of longitudinal sweep. Turn off the switches on the auxiliary panel, right to left (four switches).

22) Turn crucible to "1" to move e-beam source from sight.

23) Turn substrate index to move your samples from over the e-beam source to over the desired thermal evaporation location. The index numbers are explained on the bell jar. While the substrate is moving, a red light will be on to indicate stand-by mode, with ready indicated by a green light. Both lights are located on the lower front panel.

24) Check that the local output control is at zero on the power supply for thermal evaporation.

25) Turn on power to thermal current source.

26) The first two turns on the local output control do not do anything. After the first two turns the dial is very sensitive.

27) Turn up the current to 50 A and leave for 60 sec. Slowly turn up output to tungsten boat up to a maximum of 70 - 80 A. Do this slowly to make sure the metal does not jump out of the boat. Once the metal has melted, zero the thickness monitor and open the shutter. Using the local output control, adjust the deposition rate to ~ 6 Å/sec. After the shutter has automatically closed, return the local output control to zero.

28) Turn off the power to the thermal current source.

29) Wait for the system to cool down for 15 min.

30) When the system is cool, press "STOP" and then "VENT." Turn off the ion gauge.

31) When the system is vented, raise the HOIST.

32) Remove your materials from the CVP.

33) Replace the glass slides covering the viewing port.

34) Lower the HOIST. Slide the bell jar 1/2 in again to pick up the vacuum grease.

35) Press "START" to rough down the system.

APPENDIX D
KARL SUSS ALIGNER INSTRUCTIONS

Note: Please consult instructions located at the Karl Suss, which is in the cleanroom at the Microelectronics Building (ML). These instructions are only a guide; the ones located at the machine are more complete. You must be on the approved users' list to use the Karl Suss. Please see the student in charge for official training.

1) Clean the mask. Use acetone and isopropyl alcohol (IPA). Dry thoroughly with N_2.

2) The UV bulb should always be left on. The UV source appears as a blue light in the UV filtered cleanrooms. Most of the source is shielded, so you will only be able to see a little of the light. However, during power surges the circuit breaker may turn off the source. If so, please consult with the student in charge, John Hughes or Ray Zich at ML. There is an associated warm-up time necessary after the UV source has been turned on. Note that the UV source's lifetime is reduced every time it is turned on/off.

3) Turn on the power switch for the aligner electronics and microscope light source, located at the top of the apparatus.

4) Remove the dummy mask from the maskplate holder. Position the mask over the circular exposure area on the maskplate holder. Always place the mask with the chrome side facing up onto the maskplate holder. The holder will be inverted, placing the chrome side in contact with the substrate. Locate the correct quadrant of the mask you wish to transfer onto the substrate. Make sure that as much of this quadrant as possible can be seen through the round exposure area. Depress the VACUUM MASK switch.

5) Slide the maskplate holder over the alignment stage. Tighten the clamps to keep the maskplate holder in place.

6) Choose the proper wafer chuck. The wafer chucks have holes which are used in conjunction with the vacuum system to push the substrate toward the mask. All of the holes should be covered by the substrate. Please consult instructions located at the Karl Suss which describe the HP, ST, and Soft Contact modes. Select one of these settings.

7) Position the substrate on the exposure chuck. Slide the chuck shuttle into the alignment stage. Set the Z-Height according to the instructions located at the Karl Suss. Note that the Z-Height should never be adjusted if either the SEPARATION or CONTACT mode indicator is illuminated.

8) Select the appropriate exposure time (xx.yy h/m/s).

9) (This step can be skipped if no alignment is necessary.) To align the substrate with the mask, first move the separation slide to SEPARATION position. Use the X- Y- and Θ-micromanipulators to move the substrate. Use the black handle on the left side of the Karl Suss to move the microscope. Press the buttons on the handle to move the microscope. One button allows movement in the X-direction and the other allows movement it in the Y-direction.

10) Once alignment is complete, move the separation slide into the CONTACT position. Depress the EXPOSE button.

11) Move the contact lever back to the original position and pull out the chuck shuttle.

12) Remove substrate from the chuck.

13) Remove mask from the maskplate holder and replace the dummy mask.

14) Turn off power to the aligner electronics and to the microscope light.

APPENDIX E
PECVD INSTRUCTIONS

Note: This machine is located in the cleanroom at the Microelectronics Laboratory (ML). Proper training is required to use this machine. Your name must appear on the list of "Approved Users" to be able to use the machine. Contact the graduate student responsible for the plasma enhanced chemical vapor deposition (PECVD) system to gain approval for use. Also read the instructions located at the (PECVD) system.

1) Call the Control Room (4-4479). Tell them you are using the PECVD system, that the CDO Box is on, and which gases you will be using.

2) Vent the chamber by pressing "manual" and "vent" simultaneously. Clean the chamber with IPA, including the four glass plates. It is very important to not touch any part of the reaction vessel, except with a Kimwipe.

3) Test the CDO Box, then turn it on.

4) The clean process is necessary when a plastic glove* or other contaminant comes in contact with the reaction chamber, when a different dielectric (Si_3N_4 or SiO_2) is desired, or if 20,000 Å of the current dielectric material have been deposited. A clean is required before changing to the other dielectric process. If a clean is not necessary at this time, skip the remainder of this step and go to step 6. The complete clean process is run in two steps that should take 15 min each; however, fractions of this time may be used in proportion to the percentage of the 20,000 Å maximum. The temperature of the reaction vessel must be below 100°C, but at least 30°C. At temperatures greater than 100°C the cleaning gases will create a polymer on the reaction chamber walls. A predep is always required after a clean.

*Cleaning with a Scotchbrite pad may also be necessary; the laboratory technician in charge of the PECVD must be consulted.

5) Do a predep only after a clean. Run the process for the dielectric you wish to deposit, but without a substrate. Deposit at least 1000 Å. A predep is not necessary if a clean has NOT been performed.

6) Warm up the reaction chamber before placing your substrates inside. To start the heater manually press "manual" and "heat" simultaneously. The reaction vessel may require long periods of time to heat up to the desired reaction temperature, usually 300°C. Check the temperature setting and change, if necessary. To change the set reaction temperature, turn the key on the front panel to "CSP," press "temp," type in the correct temperature, and press "enter."

7) Vent the reaction chamber. Raise the vessel cover (press black button on top of the PECVD system ,"air," and hold the black switch in the "up" position). Load your samples into the reaction chamber. Close the reaction chamber, (press "air" and hold switch toward "down").

8) Pump down (press "manual" and "rough"). You may have to restart the heater.

9) Open gas lines. See instructions located at the PECVD system for opening the valves of the desired gases.

10) Check process parameters, ("process" "#", "step" "#", "read" "____"). The parameters are given at the PECVD. The following are not listed in the instructions located at the machine, but are also important to check:

Roughing pressure = 50 mTorr

HVAC time = 0.5 min

Pause time = 0.5 min

Vent: "0" = off, "100" = on {chose one}

Never allow automatic venting unless you will be present at the end of the process.

11) Change process parameters if necessary; (turn key to "Change Stored Parameters", select the parameter, select the new value, "enter", turn key back to "Manual Operation").

12) Run the process. (Necessary prior to pressing "run": Matchwork Box "on," ENI Box "on," proper gases open at the source.)

13) Vent the reaction chamber and remove your samples. Rough down the reaction chamber.

14) When the deposition is completed, turn off the Matchwork Box and the ENI Box. All gases must be closed off at the source. Let the reaction chamber cool down for at least 10 min and then turn off the CDO Box. Call the Control Room (4-4479) and tell them the CDO Box is off and that all gases have been shut off.

15) Fill out the log book.

APPENDIX F
AU SPUTTER INSTRUCTIONS FOR SEM

1) If the machine is off, vent the cylinder (Vent located on top of cylinder).

2) Lift the cylinder with the glass only (do not use the metal top).

3) Place the samples on the platform.

4) Move the cylinder back into place.

5) Turn on to pump down.

6) Open Ar valve.

7) Check that time is set to desired location (40 sec for glass).

8) Check that the machine is set to sputter not etch.

9) When pressure is less than 4 E -2 mbar, ready to sputter.

10) Open needle (gas leak) until the pressure meter is centered.

11) Press start.

12) Adjust current to 18 mA with the leak valve during the sputtering.

13) Close needle valve when done (be careful not to overtighten).

14) Close Ar valve.

15) Turn off.

16) Vent, then move cylinder using the glass part only.

17) Remove samples.

18) Place the cylinder over the platform and turn on to pump down.

19) Turn off before leaving.

APPENDIX G
DEFINITIONS AND TERMINOLOGY

Photoresist (PR)	Chemical which is sensitive to ultraviolet light (UV).
Substrate	The sample material upon which a pattern is placed.
Thin Film	Can be a conductor, semiconductor, or insulator and is different from bulk material in that it has a high surface-to-volume ratio, therefore, is highly influenced by surface properties.
Conductor	(Au, Ti, Al) are electrical conductors.
Semiconductor	(Si, GaAs) are usually the substrate.
Insulator	($Si0_2$,SiN_x) are usually used for crossovers.
Scribe	Process by which a substrate is broken into smaller pieces. In a semiconductor, it is usually done along a crystal plane.

APPENDIX H

SPECIFIC PROCESSING CONDITIONS

Lift-off Steps used on 7/17/93

This lift-off process is used without image reversal by using chlorobenzene to give the correct profile.

Level 1:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 photoresist (PR) and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Expose the sample for 10 sec (with black nonreflective paper on chuck).

5) Dip in chlorobenzene for 2 min at 30°C.

6) Develop in MF327 until pattern is clear.

7) Evaporate with e-beam in the CVP 200 Å of Ti.

8) Evaporate thermally in the CVP 2200 Å of Au.

9) Lift off metal on PR surface with a heated acetone soak. Ultrasound only if necessary to assist in PR removal.

10) Deposit 2000 Å of silicon nitride.

Level 2:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 PR and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Expose the sample for 10 sec (with black nonreflective paper on chuck).

5) Develop in MF327 until pattern is clear.

6) Etch in buffered HF to open via holes in the dielectric.

Level 3:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 PR and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Expose the sample for 10 sec (with black nonreflective paper on chuck).

5) Dip in chlorobenzene for 2 min at 30°C.

6) Develop in MF327 until pattern is clear.

7) Evaporate with e-beam in the CVP 200 Å of Ti.

8) Evaporate thermally in the CVP 2200 Å of Au.

9) Lift off metal on PR surface with a heated acetone soak. Ultrasound only if necessary to assist in PR removal.

Processing steps for samples 010494 A - D

This lift-off profile is achieved through an image reversal process. First the mask must be reversed, then a second image reversal is possible.

Level 1:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 PR and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Primary exposure (Karl Suss - soda lime mask) for 25 sec (C & D exposed 30 sec).

5) Reversal bake at 125°C for 90 sec.

6) Flood exposure (Karl Suss) for 45 sec.

7) Develop in MF327 for 50 sec.

8) Evaporate with e-beam in the CVP 200 Å of Ti.

9) Evaporate thermally in the CVP 2200 Å of Au.

10) Lift off metal on PR surface with a heated (LO on hotplate) acetone soak, ~ 10 min.

11) Deposit 2800 Å of silicon dioxide with the PECVD (enough to cover 2400 Å of Ti/Au).

<u>Level 2</u>:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 PR and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Primary exposure (Karl Suss - soda lime mask) for 25 sec.

5) Reversal bake at 125°C for 90 sec.

6) Flood exposure (Karl Suss) for 45 sec.

7) Develop in MF327 for 50 sec.

8) Descum in Planar Plasma Reactor for 45 sec.

9) Etch in buffered oxide etch 25 sec (A for 30 sec).

10) Remove PR: acetone, IPA, and N_2 dry.

Level 3:

1) Bakeout the slide at 110°C for 5 min to drive off any moisture.

2) Cover the slide with AZ5214 PR and spin at 4500 rpm for 30 sec.

3) Softbake the PR at 110°C for 90 sec.

4) Primary exposure (Karl Suss - soda lime mask) for 25 sec.

5) Reversal bake at 125°C for 90 sec.

6) Flood exposure (Karl Suss) for 45 sec.

7) Develop in MF327 for 50 sec.

8) Evaporate with e-beam in the CVP 200 Å of Ti.

9) Evaporate thermally in the CVP 2200 Å of Au.

10) Lift off metal on PR surface with a heated (LO on hotplate) acetone soak, ~ 10 min.

11) Alloy at 480°C for 1 min.

APPENDIX I
TESTING PROCEDURE

These procedures are for one-port testing only. Call up the program Noise Parameter Test (by Cascade Microtech) on the (HP) PC to capture data from the HP 8510B network analyzer. The captured data are saved to disk and then used to fit the model as described in the thesis body. The probe station head is moved up by rotating the knob underneath the substrate block counterclockwise. Similarly, the probe station head is moved down by rotating the knob clockwise. The probe station head should be in the up position when moving the substrate block. Use two hands to carefully move the substrate block. Move the substrate block so that the desired device can be seen through the microscope. Focus the microscope on the substrate, then lower the probe station head until a shadow can be seen. Wait a few seconds to let the system stabilize mechanically and then lower the probe station head again until the tip of the probes is in focus. Lower the probe station only until the probes slide a little across the sample. Once the device is in contact with the probe tips, it is ready for testing. The following commands describe capturing the data:

Command	Description
V	Vna sets up the computer to receive data.
F10	On this computer it is red; pressing this will start the data transfer process.
	The Smith chart from the HP should now appear on the PC screen.
Space bar	Brings the PC program back to the previous screen
ESC	Will change menus on PC program and allow the user to choose save.

S	Choose save from the screen menu.
"filename"	Type the filename under which you wish to save your data.
F10	(Red button), press this instead of *ENTER.*
ESC	This completes the save routine. Move to the next coil and follow this procedure for each device.

The overall layout of the coils with respect to the alignment markers for the mask designated NEWGEOM is illustrated in Fig. I.1.

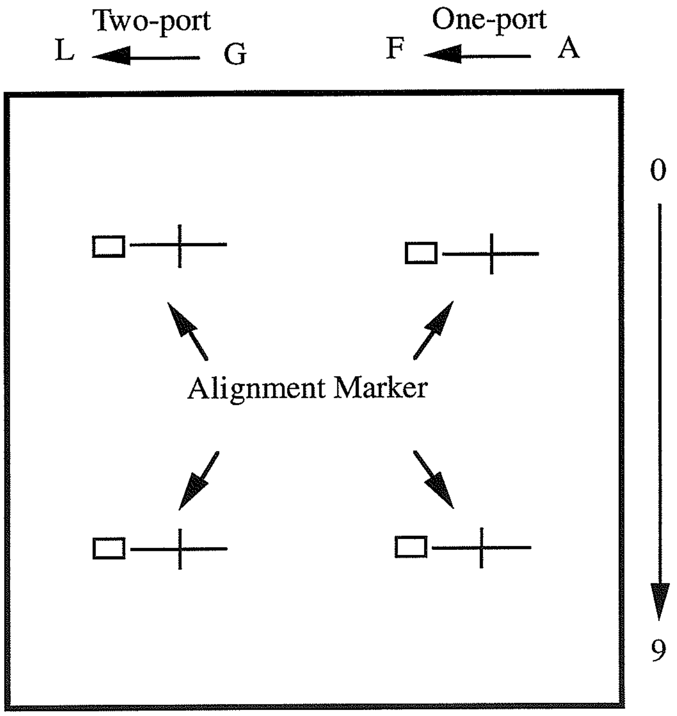

Fig. I.1 Coil Layout Scheme with Respect to Alignment Markers

REFERENCES

1 E. Odeblad, *Micro-NMR In High Permanent Magnetic Fields* (Karolinska Institute Dept. of Obstetrics and Gynecology, Stockholm, 1966).

2 Z. Cho, C. Ahn, S. Juh, and H. Lee, Med. Phys. **15** (6), 815 (1988).

3 X. Zhou, C. Potter, P. Lauterbur, and B. Voth, Abstracts, 8th Annual Meeting SMRM, Amsterdam, 286 (1989).

4 J. Travis, Science **263**, 610, (4 Feb.1994).

5 X. Zhou, R.L. Magin, J.C. Alameda Jr., H.A. Reynolds, and P.C. Lauterbur, Magnetic Resonance in Medicine, 92, (1993).

6 T.L. Peck, R.L. Magin, and P.C. Lauterbur, Abstracts, 9th Annual Meeting of the SMRM, 207, (1990).

7 T.L. Peck, Ph.D. thesis, University of Illinois at Urbana-Champaign, 1992.

8 D. Hoult and R. Richards, J. Magn. Reson. **24**, 71 (1976).

9 D. Hoult and P. Lauterbur, J. Magn. Reson. **34**, 425 (1979).

10 W. House, IEEE Trans. Nucl. Science **31**, 570, (1984).

11 S. Wolf and R.N. Tauber, *Silicon Processing for the VLSI Era Volume 1: Processing Technology*, (Lattice Press, California, 1986), pp. 407-408, 493-504.

12 I. Amato, Science **258**, 1084, (13 Nov. 1992).

13 J.L. Novak and B. C. Wheeler, IEEE Trans. Biomed. Eng. **BME-33** (2), 196, (1986).

14 S. Boppart, B.C. Wheeler, and C.S. Wallace, IEEE Trans. Biomed. Eng. **39**, (1), 37, (1992).

[15] R.E. Williams, *Gallium Arsenide Processing Techniques* (Artech, MA, 1984) pp. 143-145.

[16] T.L. Peck, R.L. Magin, L. LaValle, I. Adesida, and P.C. Lauterbur, Abstracts, 12th Annual Meeting of the SMRM, New York, 296, (1993).

[17] T.L. Peck, L. LaValle, R.L. Magin, I. Adesida, B.C. Wheeler, and P.C. Lauterbur, Abstracts, 2nd International Conference on Magnetic Resonance Microscopy, Heidelburg, Germany, 90, (1993).

[18] T.L. Peck, L. LaValle, R.L. Magin, I. Adesida, B.C. Wheeler, and P.C. Lauterbur, Abstracts, 15th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, San Diego, (1993).

[19] *Handbook of Optical Constants*, pp. 771-774, 1985.

[20] G.E. Anner, *Planar Processing Primer* (Van Nostrand Reinhold, New York, 1990).

[21] C.A. Mack, J. Electrochem. Soc.: Solid-State Science and Technology, 148, (1987).