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# FABRICATION PROCESS FOR ELECTROABSORPTION MODULATORS

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This report focuses on the fabrication aspects of Electroabsorption Modulator (EAM) devices developed by the University of California at San Diego (UCSD). Air Force Research Laboratory (AFRL) SNDP personnel learned the processes directly at UCSD with the primary goal of transitioning the process to AFRL/SNDP. EAMs were designed to operate at 1550 nm using Indium Phosphide (InP) technology with semi-insulating wafers purchased from Tee Wel (Taiwan). Most of the process uses negative photoresist and is an 8-step mask procedure. The final metal coating is most critical to making robust n- and p- contacts. Without good metallization, wire bonding into a package fails. This report acts as a recipe aid to EAM device fabrication. Various times, levels, temperature, etc., quoted in this report were determined after careful calibration studies for each processing step and should only be used as guide values. Parameters change as materials age and machines change.

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## Introduction

The development of Photonic RF Links continues to be of great interest to Air Force platforms that require extremely high spur free dynamic range (SFDR) in such systems as Global Hawk, D-II and JSF, and even higher requirements for recon aircraft. The key bottleneck to achieving such performance in a link lies with the electro-optic modulator.

There are at present two candidate schemes for analog fiber-optic links: one that uses a directly modulated laser diode, and one that uses externally modulated laser light. The direct modulation scheme is attractive mainly because of the availability of various laser diode sources. The main shortcomings of direct modulation schemes are the laser intensity noise that affects the dynamic range and noise figure and the high laser efficiency required for achieving RF transparency. To date fiber optic links using direct modulation suffer RF loss that necessitates the use of signal preamplifier at the transmitter and/or signal post amplifier at the receiver, both of which are not ideal for system performance. On the other hand, fiber-optic links based on external modulation of a high power, low intensity noise laser can provide improvement in both RF link gain and link linearity as the laser power increases. For an externally modulated link, a high speed electroabsorption modulator (EAM) with high saturation optical power is currently of interest because of its size, efficiency, bandwidth and ease to monolithically integrate with a laser. EAMs naturally lend themselves to remote assemblies and large array antennae systems due to their size and weight.

Electroabsorption effects denote the change of the optical absorption coefficient in materials due to the presence of an electric field. EAMs using multiple-quantum-well (MQW) active layers have been popular as they typically possess a large absorption-coefficient change with applied electric field. Various research programs have furthered the development of EAMs by improving the power handling, bandwidth, linearity and insertion losses[1-3].

Implementation of EAMs outside of a laboratory environment will be gated by the development of effective processing and packaging methods. This report focuses on the fabrication aspects of EAM devices developed by the University of California at San Diego (UCSD). AFRL/SDNP personnel learned the processes directly at UCSD with the primary goal of transitioning the process to AFRL/SNDP. EAMs were designed to operate at 1550 nm using Indium Phosphide (InP) technology with semi-insulating wafers purchased from Tec Wel (Taiwan). Most of the process uses negative photoresist and is an 8-step mask procedure. The final metal coating is most critical to making robust n- and p-contacts. Without good metallization, wire bonding into a package fails. This report acts as a recipe aid to EAM device fabrication. Various times, levels, temperature, etc. quoted in this report were determined after careful calibration studies for each processing step and should only be used as guide values. Parameters change as materials age and machines change.

## A. Mask Definitions

Eight masks are used in the fabrication process. Discussion in how to make masks is not discussed here but a description is provided. For efficiency four masks are designed and arranged in quadrants on a 5” mask plate in quadrants. Table 1 describes each processing step by quadrants with each mask name, mask type, and mask function.

**Table 1 - Mask Processing Steps**

| **Mask A:** | **Name** | **Type** | **Function** |
|---|---|---|---|
| Quadrant I | P-Metal Contact | Bright Field | Defines p-metal ridge area, creates by lift off. |
| Quadrant II | Waveguide (WG) Mesa | Dark | Defines WG mesa area with photoresist which protects area from the etching. |
| Quadrant III | Large Optical Core (LOC) | Dark | Defines LOC area with photoresist which protects area from the etching. |
| Quadrant IIII | BCB-1 | Dark | Defines and creates encapsulation area with BCB |
| **Mask B:** | | | |
| Quadrant I | Mask II-B | Bright | Defines N-metal contact pads, creates by lift off |
| Quadrant II | BCB-2 | Dark | Defines bridge area for signal contact with BCB |
| Quadrant III | Signal Pad | Bright | Defines p-metal signal contact pads, creates by lift off |
| Quadrant IIII | Ground and Signal Pad | Bright | Used for electroplating thick gold on pads |

Each mask throughout the fab process must be inspected and cleaned using sequential rinses in room temperature acetone, methanol, and IPA.

## B. Preparing the Wafer

The first step involves preparing the wafer by cleaving into small 1 cm x 1 cm pieces. A fabrication (fab) run with two samples is always necessary in case something happens to one sample. The back of the wafer is examined under a microscope before cleaving. The lattice domains line up in one direction. The wafer is cleaved parallel and perpendicular to these domains. The masks for making the electrode waveguides need to be aligned parallel to the domains shown in Figure 1.

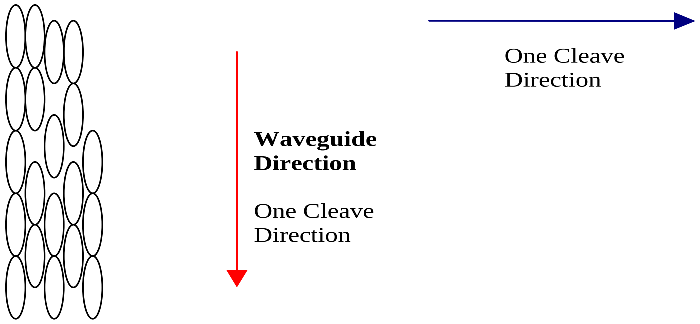


**Figure 1 - Substrate Cleaving**

The polished side of the wafer is the side to be processed. A representative layer structure for EAMs grown on an InP substrate is shown in Figure 2.

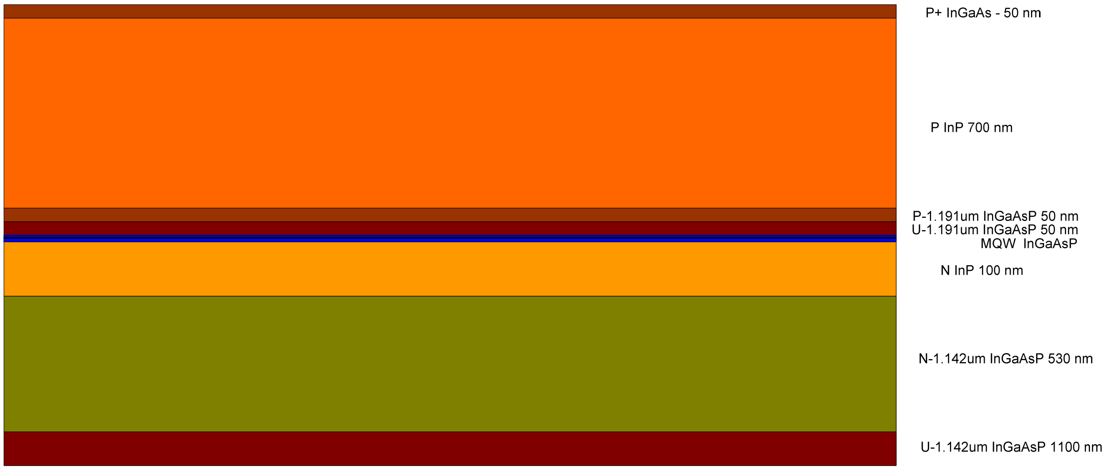


**Figure 2 - InP Based Layer Structure**

Initial cleaning of the samples is done with a series of bath solutions: an acetone bath at 130 degrees C for 5 minutes, followed by a methanol boiling bath at 130 degrees C for 5 minutes, concluding with an Isopropyl Alcohol (IPA) rinse. The sample is then rinsed in deionized (DI) water for 5 minutes and blown dry with nitrogen ($N_2$) gas.

An additional acid dip in buffered oxide etch (BOE) is necessary for 30 seconds to remove any oxidation layers from the wafer, followed by a flowing rinse in DI water for 3 minutes and blown dry with $N_2$. After completing these steps, the samples are ready for processing.

## C. Metal Electrode-Waveguide Contact Definition

The first process is to make the p-metal contact electrode. This metal becomes the top surface of the waveguide structure using the bright field mask labeled P-Metal Contact and consists of parallel 1.5 μm wide waveguides shown in Figure 3. Negative photoresist is applied to the samples using spin coating techniques, and the particular photoresist chosen, Futerrex NR7-1000PY, is 1 μm thick with cutback properties shown in Figure 4 that allow for easier liftoff.

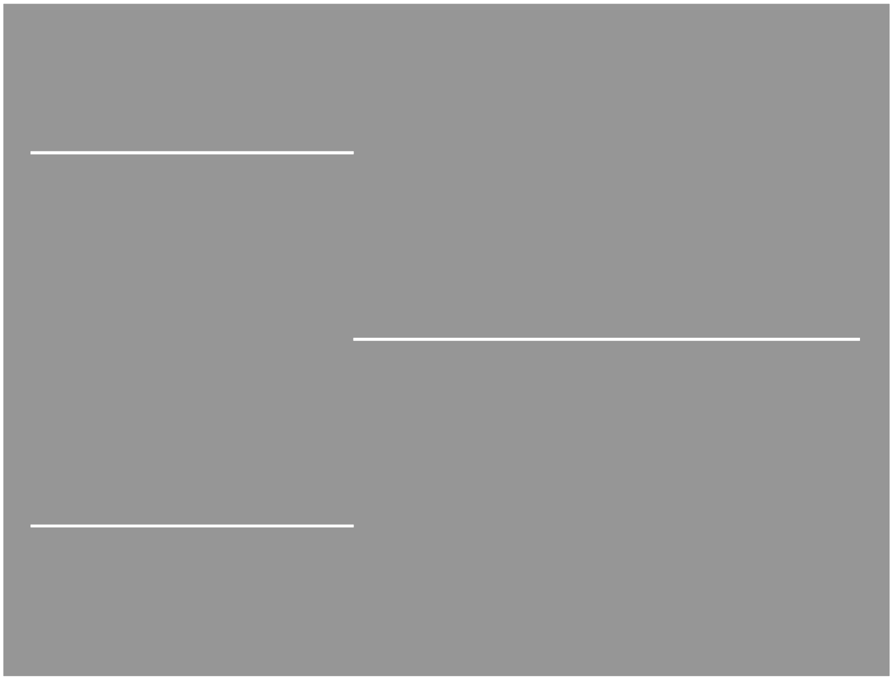


**Figure 3 – P-Metal Electrode-Waveguide Contact Mask**

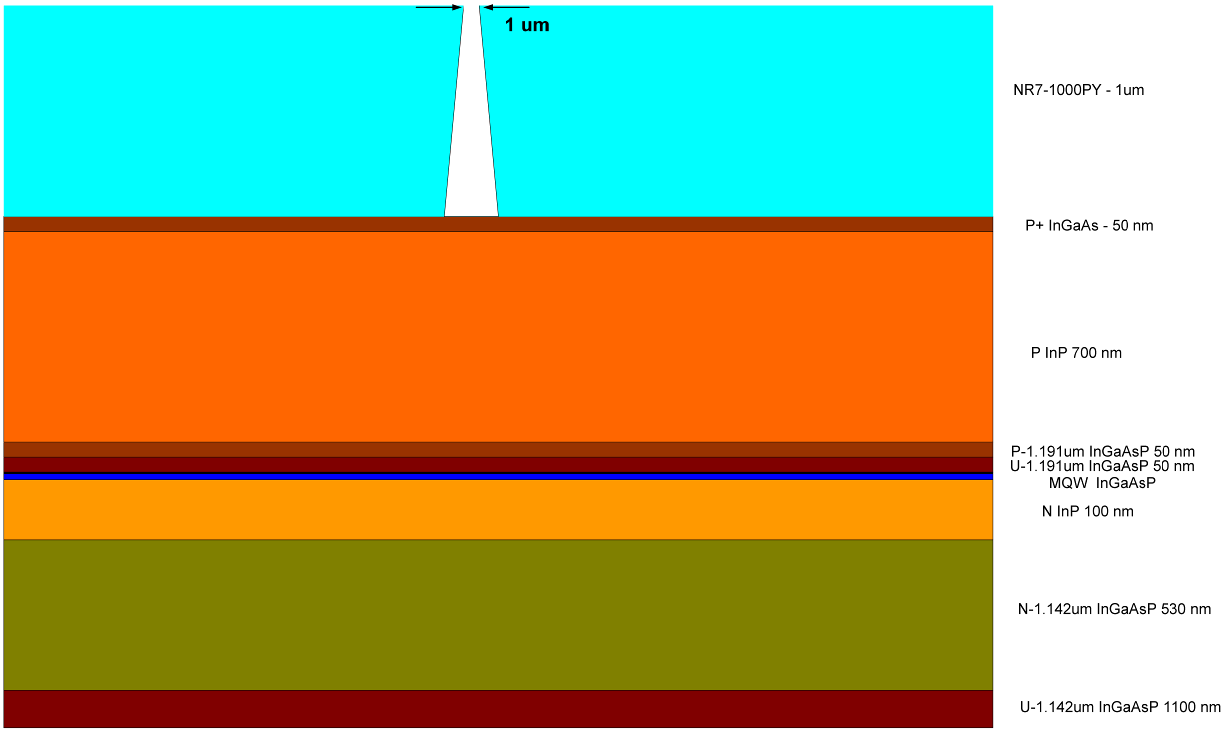


**Figure 4 - Cutback Characteristics of NR7-1000PY Photoresist**

The sequence for preparing the sample for the photoresist is as follows:

1. Pre-bake the sample at 120 degrees C for two minutes.
2. Clean the spinner chuck with acetone and blow dry.
3. Cover the entire sample with photoresist taking care that no photoresist flows under the sample; otherwise this will be a source for problems later in the processing.
4. Spin the sample at 4000 RPM for 40 seconds.
5. Remove the sample from spinner and bake at 150 degrees C for 70 seconds.
6. Samples are now ready for exposure.

Exposure characterization is performed to determine the correct time using a photoresist coated blank silicon wafer. Over exposure creates thinner features on the photoresist, while under exposure creates larger features.

Once the exposure time is optimized, alignment of the P-Metal Contact mask to the sample occurs. **The electrode structures must be aligned with the cleave edge parallel to the InP domains**. It is important to align multiple structures to the cleaved edge not just one ensuring that the entire sample is in contact with the mask. Interference fringes are visible on all for corners of the mask when there is contact. It is critical that the entire mask makes contact with the sample, and if it doesn't, proper adjustments to the table and sample holder become necessary. Once complete contact is made, the sample is exposed to the UV light.

Immediately after the exposure, the sample is pre-develop baked at 100 degrees C for 70 seconds on a hot plate. The sample is then removed from the hot plate and allowed to cool for a few minutes. Failure to allow the sample to cool will cause it to break or shatter from thermal shock. The cooled sample is then inserted into RD-6 developing solution, soaking it for 10 seconds. The sample needs to go through a flowing DI water rinse for 5 minutes best achieved by placing the sample into a beaker and allowing the water to flow into the beaker for 5 minutes. The samples can be examined under a microscope to see the approximate width of the channels in the photoresist which may also be checked with a profilometer.

Next the sample needs to go through a descum process using an $O_2$ plasma asher. By controlling the parameters of RF power, chamber pressure, gas flow, and exposure time, plasma chemistry can induce useful changes to a substrate surface. Descumming removes particles remaining on the sample before the metal layer is applied. To descum the was pressure set to 200 mT of $O_2$ and the RF power set to 200 W for 120 seconds.

## D. P-Contact Metal Deposition

An electron beam (e-beam) evaporator should be used for metallization. The choice of p-metal consisting of Palladium/Titanium/ Palladium/Gold (Pd/Ti/Pd/Au) is driven by the necessity to bring the overall ohmic contact resistance down as much as possible, the total area is small so it is important to keep the specific resistance to below 1e-5 Ohm-cm. Measured values during this step were in the upper 1e-6 Ohm-cm. If values with traditional Titanium/ Platinum/Gold (Ti/Pt/Au) contacts are of a similar order then certainly the combination can be used as well. Sequentially 50 nm of Pd, 100 nm of Ti, 100 nm of Pd, and 1500 nm of Au were deposited under high vacuum. The procedure should not be rushed, and the sample needs to cool before removing them from the evaporator.

The unwanted metal on the samples lifts and separates off by soaking the samples in acetone anywhere from 30 minutes to overnight. After lift off, the remaining gold electrode can be examined under a microscope. The ridges should be 1.5 μm (as designed) otherwise the exposure was wrong. A schematic is shown in Figure 5. The metal thickness should be measured using a profilometer and should be within 10% of the growth target. The accuracy of the profiler tip must be considered, and in this case, the electrode height was measured to be 177 nm.

The samples need to be re-cleaned using an acetone bath at 150 degrees C for 30 minutes and a room temperature methanol and IPA rinse. To avoid residue the sample must be very wet from the IPA as it is dried with $N_2$. Another descum of the samples in the plasma asher is necessary with the settings at 200 mT and 200 W for 120 seconds.

**Figure 5 – P-Metal Electrode Contact for Waveguide Structure**

## E. Ohmic Contact Development

This process turns the deposited metal into ohmic contacts by a baking process in a rapid thermal annealer (RTA) and is a very important step to making the devices work. The system was calibrated to ensure the baking time created the proper resistance needed. Purging the RTA chamber first with $N_2$ for 15 minutes drives out any moisture. The samples are baked in the RTA in a forming gas environment, $H_2$:Ni; 5%:95%, at 350 degrees C for 60 seconds. The samples must be cooled down in the RTA before removing.

The sample should be examined under a microscope to look for damaged metal which is indicated by color changes and/or bubbling under or on the metal.

Squares were patterned on the sample from first mask which act as ohmic test squares. Using a probe station, the resistance of the metal across the sample can be measured by probing across square to square. Using a parametric analyzer, the current-voltage (I-V) response should be a linear trace.  If it is flat, the ohmic contacts do not work and the sample is useless.

## F. Mesa Waveguide Patterning

Negative photoresist NR9-1500P is designed to give a 1.5 μm thick layer, less cutback, and is designed for 2-3 μm features. It should be tested on a blank Si sample to achieve the required thickness.  Here it was spun on at 4000 RPMs for 40 seconds and baked at 150 degrees C for 70 seconds.

The Waveguide Mesa mask is a dark field mask, shown in Figure 6, and defines the mesa waveguide structure. The mesa waveguide is 2-3 μm in width and created by later etching the sample to a depth of 850 nm. The mask should be cleaned in an acetone, methanol and IPA rinse. Using the mask aligner, the large crosses on the mask are used for course alignment. Finer alignment marks near the cross pattern allow finer alignment of the waveguides to the metal alignment structures. Of course, these alignment structures may be different based on who designed the mask. The waveguide structure is designed to be longer than the metal contact deposited.

Once this alignment is complete and all four corners are in contact with the mask, the exposure can begin. Note: The exposure time is different since a different photoresist is used in this step which was precalibrated on a Si test blank. After exposure the sample is pre-develop baked at 100 degrees C for 70 seconds. When it is fully cooled the sample is soaked in RD-6 developer for 10 seconds, rinsed with flowing DI water for 5 minutes, and blown dry with $N_2$.

A pre-etch bake is necessary at 150 degrees C for 60 seconds. This heating is designed to reflow the photoresist which reduces the sharpness or noise of any edge feature. The developed photoresist pattern is shown in Figure 7.

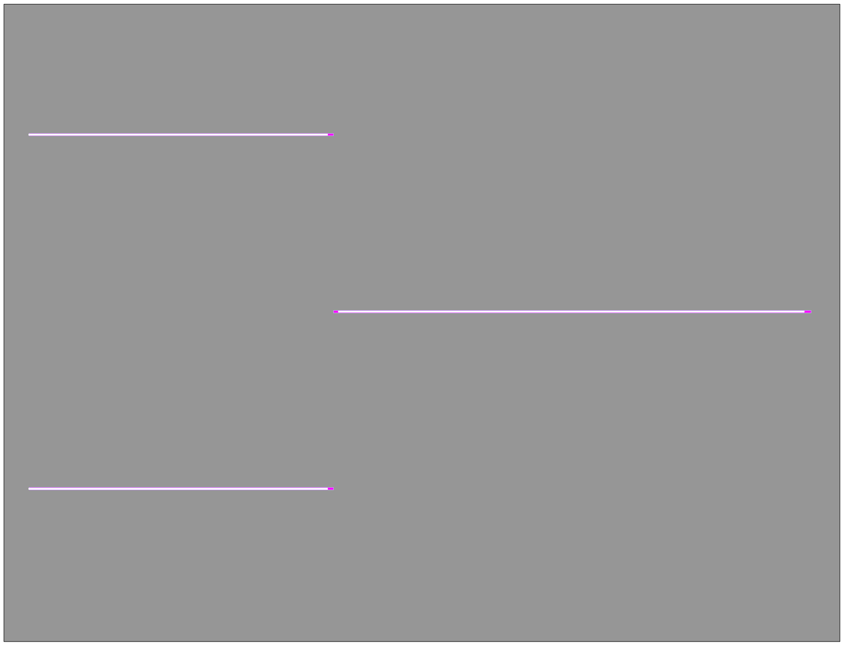


**Figure 6 - Mesa Waveguide Mask Design**

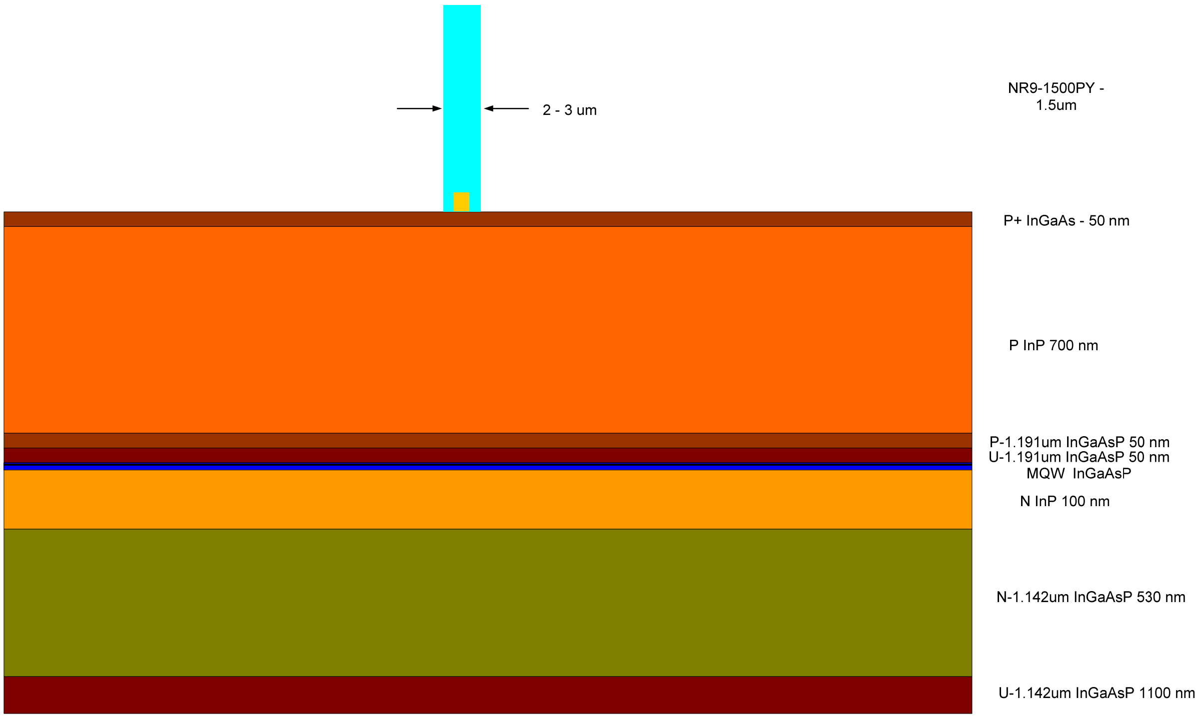


**Figure 7 - Developed Photoresist from Mesa Waveguide Mask**

## G. Waveguide Wet Chemical Etch

The ridge waveguide is created by a series of wet etches. The first InGaAs layer (50 nm) is etched with the $H_3PO_4$:$H_2O_2$:$H_20$ (1 ml:1 ml:38 ml) solution for 45 seconds followed by a 5 minute rinse in flowing DI water and blown dry with $N_2$. The InP layers (700 nm) are etched for 60 seconds with a HCl:$H_3PO_4$ (3 ml:5 ml) solution, rinsed with flowing DI water for 30 minutes and blown dry.

The two InGaAsP layers are etched off using a bromine based etch (bretch) and is comprised of $H_2O$:HBr:$Br_2$ (50 ml:10 ml:10 drops) solution for 60 seconds, rinsed with flowing DI water for 5 minutes and blown dry. Bretch is nonselective, and care must be taken when etching these layers since there is no etch stop which could result in the MWQ active layer etching away if not properly timed.

Other people have used different wet etches combinations which would work just as well such as HCl:$C_2H_4O_2$ (1 ml:4 ml) for InP over InGaAs or InGaAsP and $H_2SO_4$:$H_2O_2$:$H_2O$ (1 ml:1 ml:10 ml) for InGaAs over InP, as long as the etch times were adjusted correspondingly. UCSD's experience showed that bretch was preferred over other etches for structures having no etch stop because it leaves a better smooth and uniformly etched surface forming the waveguide sidewall.

The sample needs to be cleaned and stripped of the remaining photoresist using the standard room temperature acetone soak for 30 minutes, methanol and IPA rinse method and followed by a 5 minute flowing DI water rinse and $N_2$ blow dry. The etch depth measured with the profiler shows a mesa depth of 850 nm depicted in Figure 8.

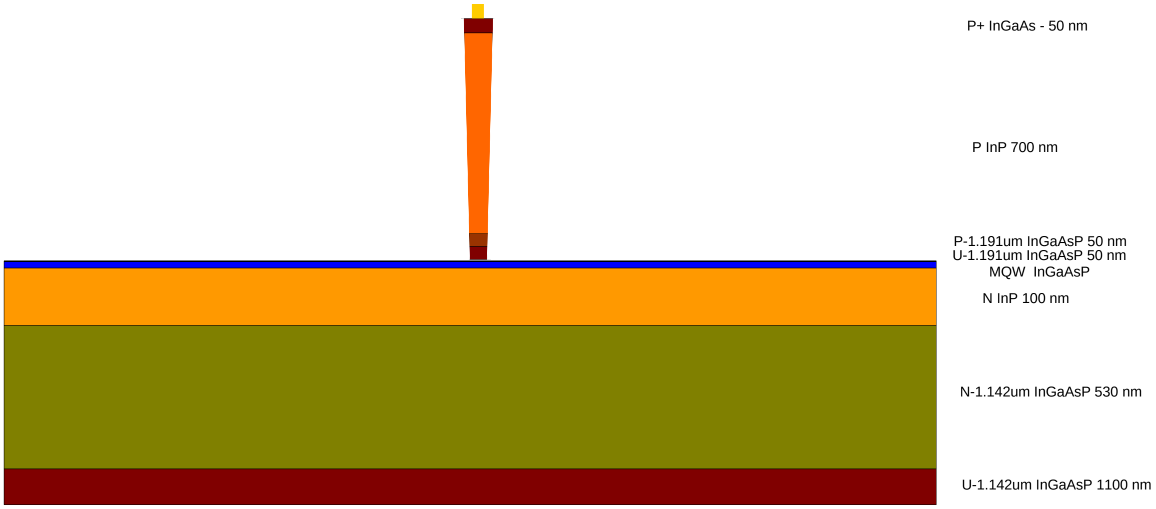


**Figure 8 - Etch to an 850 nm Depth**

## H. LOC Patterning

This section defines the large optical core (LOC) waveguide. A 14-16 µm wide waveguide (+/- 7-8 µm) about the 2-3 um waveguide acts as the optical confinement area for the buried mode. The LOC labeled mask, shown in Figure 9, is used in this step and is a dark field mask.

Negative photoresist, NR9-1500P, is spun on the sample at 4000 RPM for 40 seconds and baked on a hot plate at 150 degrees C for 70 seconds. The mask is aligned to the sample using the course and fine adjustments and exposed. After exposure the sample is baked at 100 degrees C for 70 seconds. When it is fully cooled the sample is soaked in RD-6 developer for 10 seconds, rinsed with flowing DI water for 5 minutes, and blown dry with $N_2$.

A pre-etch bake is necessary at 150 degrees C for 60 seconds to reflow the photoresist to smooth the noise of any edge feature along the inner edge of the waveguide. A descum of the photoresist is performed in the plasma asher with standard settings of 200 mT of $O_2$ and 200 W for 120 seconds. At this point the sample is prepared for the next etch sequence.

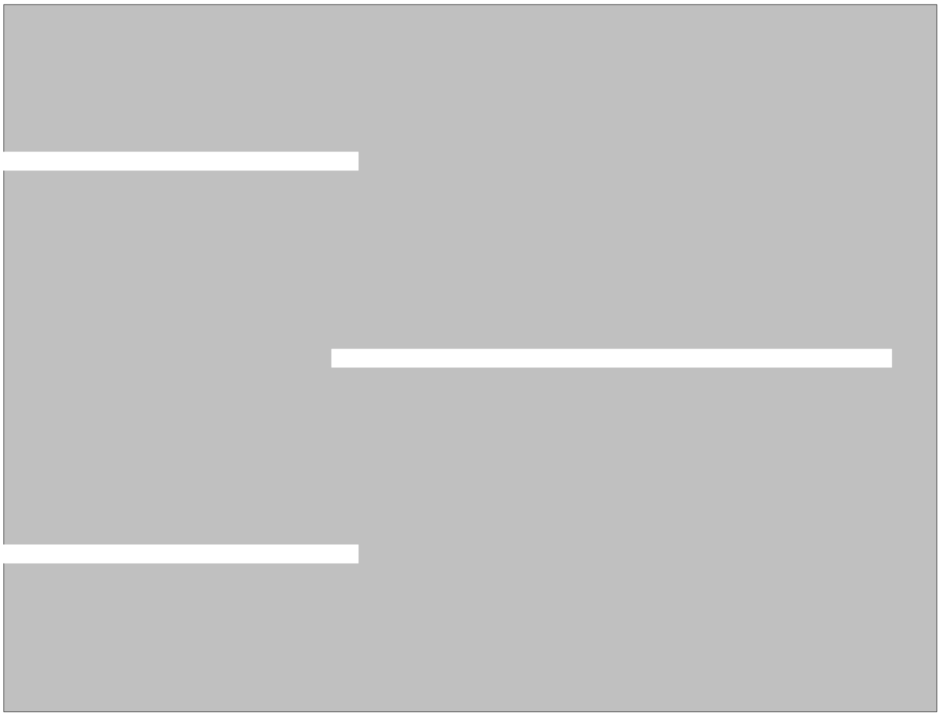


**Figure 9 - LOC Mask**

## I. LOC Wet Etch

This fab step etches the InGaAsP MQW and InP layers (300-350 nm) and creates the ridge LOC waveguide. The desired characteristic of this step is to have a very sharp etch exactly at the edge of the defined waveguide. The bromine based etch ("bretch") solution is comprised of $H_2O:HBr:Br_2$ (50 ml:10 ml:10 drops) and is a nonleveling etch meaning it goes deeper by the masked feature, and as the lateral distance increase from this edge, the etch depth decreases and becomes noisy, or less consistent. When the LOC is formed with bretch by etching down ~ 300 nm at the masked feature, the remaining bulk of the sample, in the area where the n-contacts would fall into, is etched merely ~150 nm which corresponds to the active area MQW layer remaining semi-insulating. This is unacceptable, so the etch is continued further down to the n-doped layers where it becomes non-critical where the etch is stopped. It is at the n-doped layers where ohmic contacts are formed. This etch must be completely understood, and an SEM scan will show the exact profile of this etch.

With care a profiler can be used to measure the sidewall height if there is a complete understanding of the instrument and its stylus. Figure 10 depicts the desired etch profile. The etch along the waveguide wall measured approximately 250 nm shown in Figure 11, but since the head of the profiler was 10 nm, it could not accurately measure the actual depth of this etch which is estimated to be realistically closer to 300 nm. The figure illustrates how the etch becomes noisy moving away from the waveguide wall.

The remaining negative photoresist must be stripped with a room temperature acetone, methanol and IPA rinse followed by a rinse in DI water for 30 minutes and blown dry.

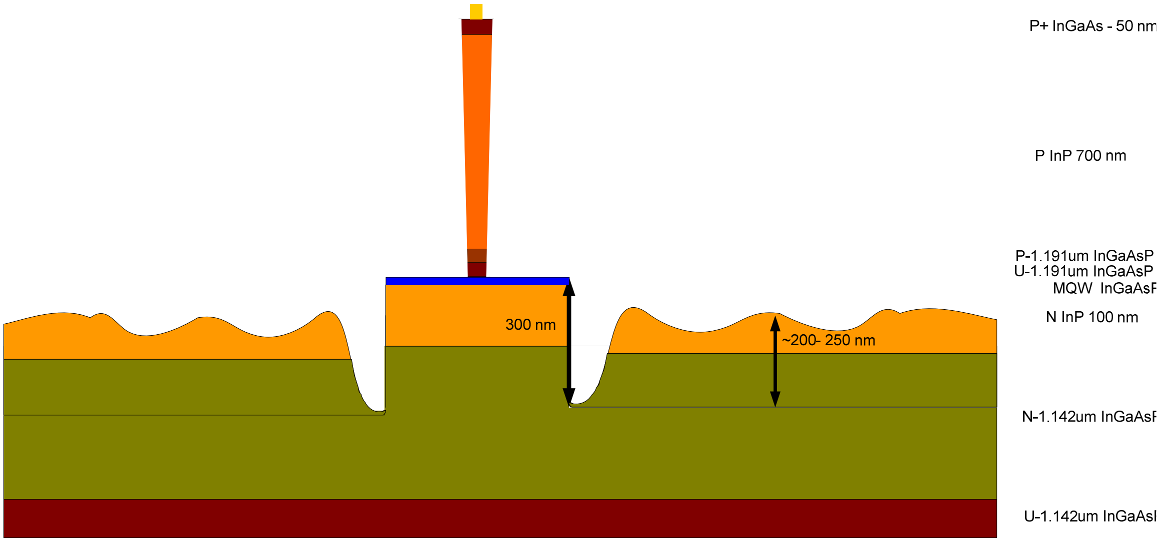
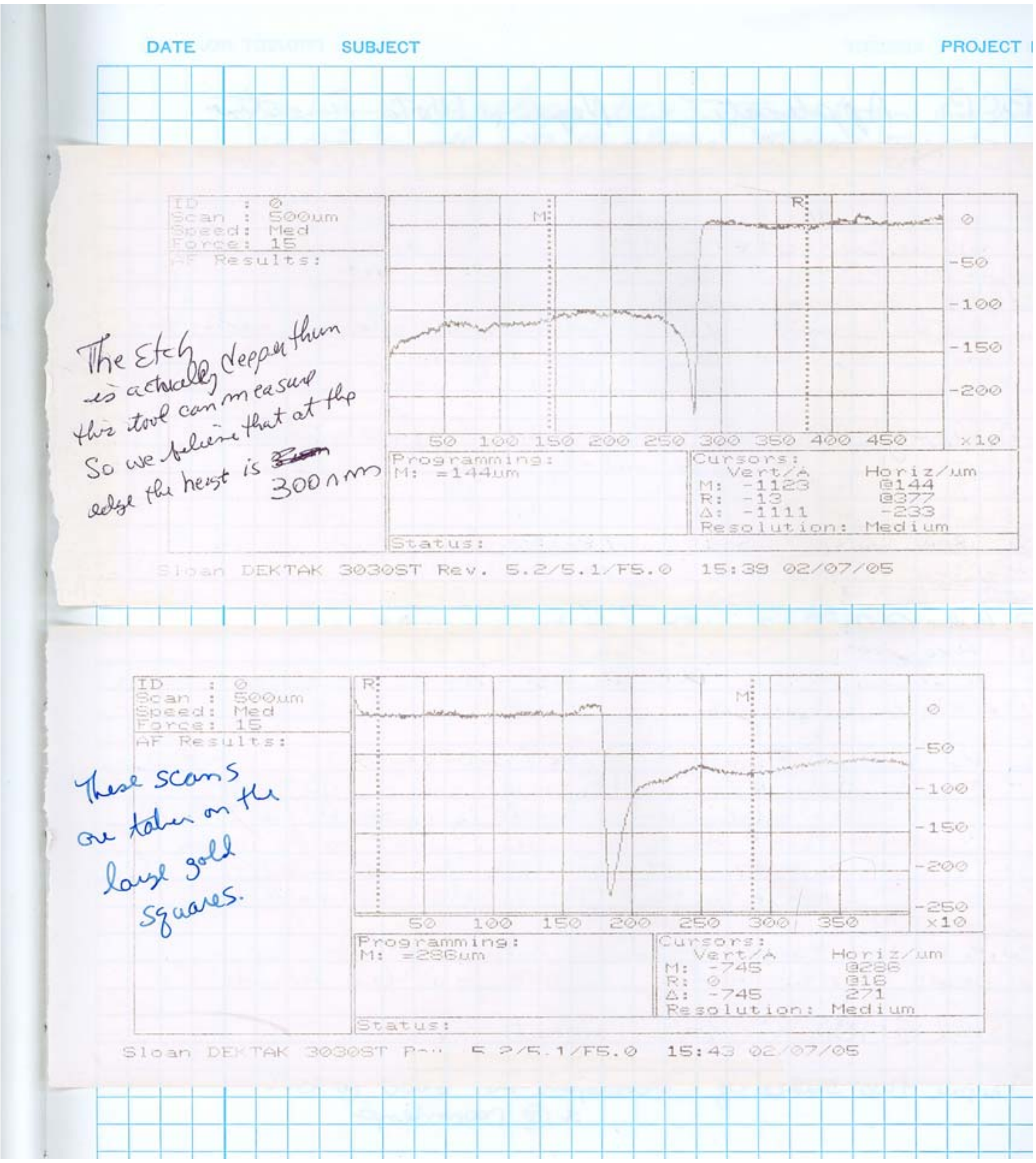


**Figure 10 – N-Doped InP Etch - 300 nm Deep**



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Programming:
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Cursors:
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M:  -1123            @144
R:  -13              @377
Δ:  -1111            -233
Resolution:  Medium

Status:

Sloan DEKTAK 3030ST Rev. 5.2/5.1/F5.0   15:39 02/07/05
```

The Etch is actually deeper than this tool can measure So we believe that at the edge the height is 300nm

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Cursors:
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Δ:  -745             271
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These scans are taken on the large gold squares.

**Figure 11 – Profile of Etch Depth**

## J. BCB Application for Mesa Encapsulation

This process forms the waveguide encapsulating block and the p-metal opening simultaneously. A negative photosensitive polymer called cyclotene is also known as BCB and is supplied by DOW Chemical; its web site is www.cyclotene.com. The BCB layer primarily acts as protection for the waveguide and provides sidewall passivation. The properties of the polymer change and degrade with time resulting in a shelf life of two years and must be kept in the freezer to prolong its lifetime. This step is difficult and can be time consuming. Before use the BCB must be brought up to room temperature. It is important to make sure no bubbles are present in the BCB as it may cause problems later in the processing.

**Before applying any BCB to the actual sample, several test runs on a blank Si wafer should be done to ensure the BCB processing will be successful.** BCB thickness can be altered by diluting with a solvent creating a thinner layer. Spin rate also affects the thickness; slower gives a thicker layer, and faster gives a thinner layer. Full characterization needs to be performed.

The BCB-1 Mask, shown in Figure 12, is a dark field mask and must be properly prepared. Some residual BCB contamination may be on the mask from a previous alignment and must be cleaned by soaking for 15 minutes in Primary Stripper A. A generous rinse with IPA and blow dry with $N_2$ completes the cleanse.

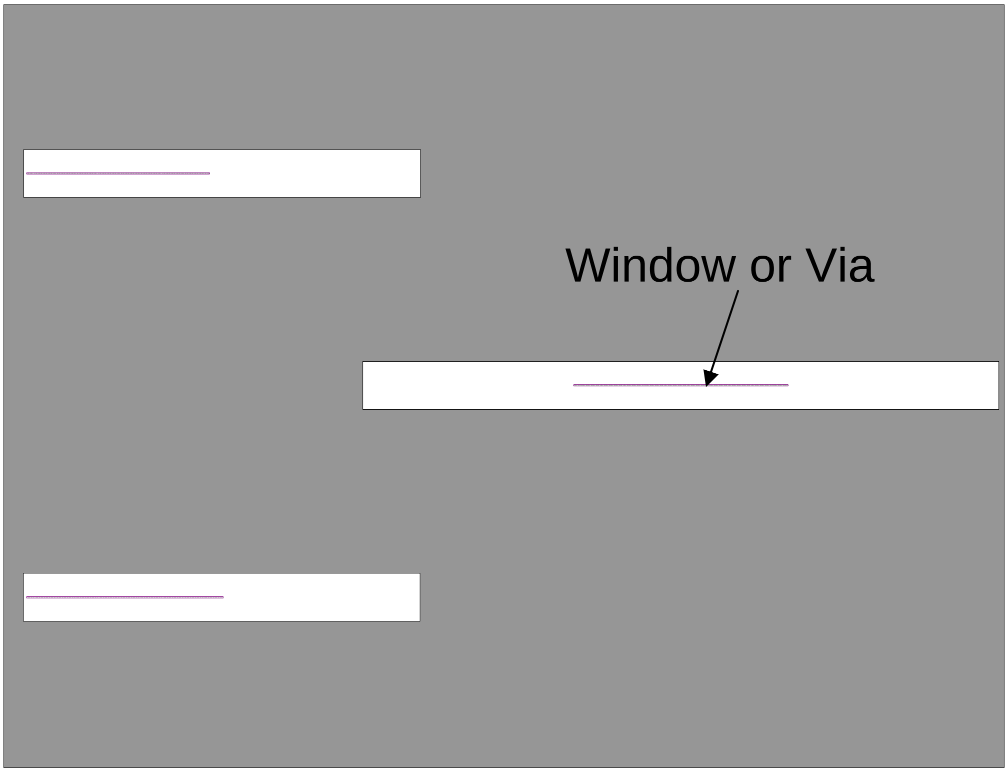

**Figure 12 – BCB-1 Mask**

The test run procedure for a BCB on silicon to determine the right exposure follows:

a) BOE etch the Si samples for 10 seconds.
b) Rinse in flowing DI water for 5 minutes and blow dry with $N_2$.
c) Apply AP-3000 @ 3000 RPM for 30 seconds, a BCB adhesion assist layer.
d) Spin the BCB on the sample with the following ramp characteristics; 500 RPM for 10 seconds, 1000 RPM for 10 seconds, 4000 RPM for 40 seconds.
e) Bake @ 90 degrees C for 3 minutes.
f) Expose the BCB-1 mask (or a specialty characterization mask that has arrays of features) at required energy density or time. Under exposure results in very thin features and over exposure washes out the features. Several exposures may be needed to find the proper time. No special alignment is necessary, only good contact of the entire sample with the mask.
g) Develop in heated DS-3000 @ 35 degrees C for 30 seconds. The development can be watched; when the sample stops changing colors leave in for about 3 more seconds.
h) Submerge in room temperature (RT) DS-3000 for 1 minute and agitate with a pipette. This will loosen any BCB material that needs to be removed at this time.
i) Place the sample on the spinner, while wet from the DS-3000 spin @ 2000 RPM for 2 minutes. Simultaneously blow dry with $N_2$ until the DS-3000 is actually removed from the sample. At room temperature the DS-3000 develop rate is insignificant and does not require rinsing. It should only be spun with $N_2$ forcing the developer off the sample thereby drying it. This developer will not dry or wash away with water so be very careful with contamination.
j) Bake @ 90 degrees C for 1 minute.
k) Examine the test features under the microscope. If everything has gone right, it will look like Figure 12 if using BSB-1 mask or Figure 13 if using a BCB characterization mask.

The windows, or vias, should be well defined and colors, or interference fringes, from a thin film of BCB should be visible. The BCB windows must not be too wide; they should be slightly narrower than the metal strips. If they are wider, they can result in electrically shorting out the top layers of the waveguide later in the process. If the exposure was underexposed, the windows would not exist or be partially visible because the exposure did not penetrate enough. If the sample was overexposed, the windows would be larger than designed.

The outer edges of the BCB area should be fairly well defined with little to no edge rounding. If the encapsulation BCB has lots of colors, it indicates that it is too thin. The correct thickness is between 2.5 – 3.2 μm.

Figure 13 shows a series of gold strips that increase in width by 1 μm. This was to simulate the window area of the BCB-1 mask and determine the necessary exposure time to make good edges. The figure shows a properly exposed and developed pattern. The light grey/blue area is the exposed Si sample after development and cleaning.

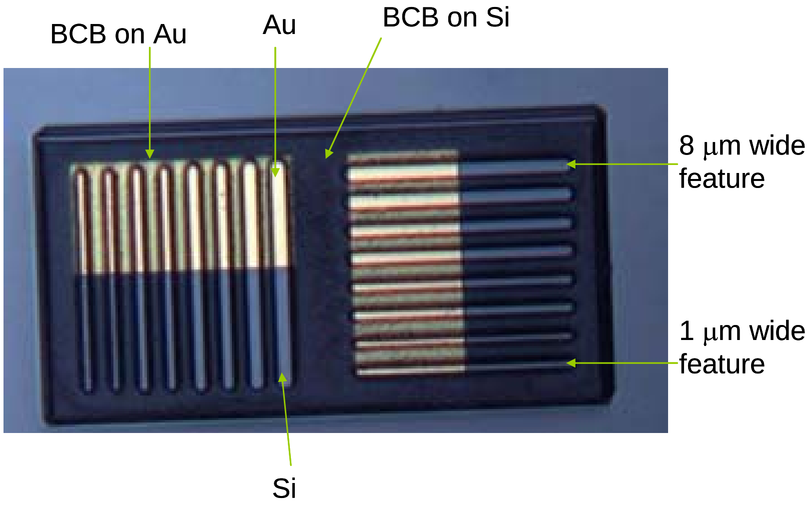

Figure 13 - BCB Test Pattern Showing a Good Exposure

Once the proper recipe for the BCB is determined, the actual sample can be coated with the adhesion layer AP-3000 @ 3000 RPM for 30 seconds. As mentioned in the test run, a second application of this may be needed if the BCB is not sticking to the surface. The BCB is applied using the three different rotations: 500 RPM for 10 seconds, 1000 RPM for 10 seconds, and 4000 RPM for 40 seconds. It is baked on hot plate at 90 degrees C for 3 minutes, cooled and aligned with the BCB-1 mask that was cleaned using a soak for 15 minutes in Primary Stripper A, generously rinsed with IPA, and blown dry with $N_2$.

Alignment of this mask is crucial and is the most difficult of all the masks. To understand better, at the end of this processing step, the entire device will be encapsulated in a 30-40 μm wide, 3 μm high layer of BCB with an opened window in the center to allow the p-metal contact to be exposed. The important detail is that the window or via in the BCB-1 mask aligns perfectly over the gold contact feature. It will be slightly smaller in width than the gold. If the window is off in lateral alignment, the gold deposited later in the process will short out the waveguide stack. Figure 14 shows the alignment mark which allows the BCB window to align the metal contact and center it on the mesa waveguide.

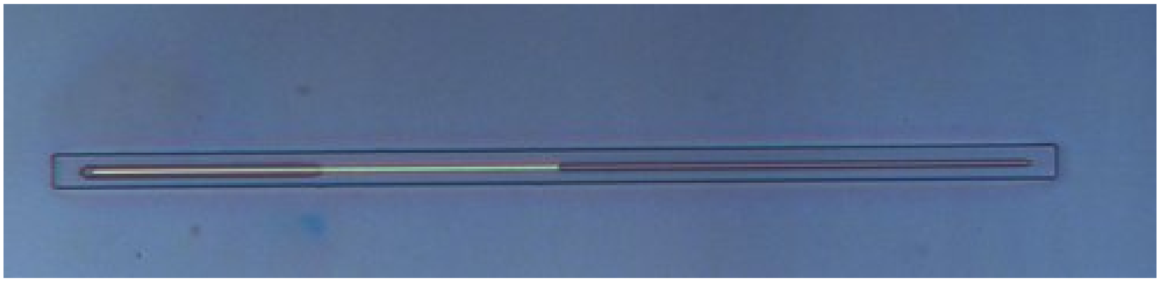

Figure 14 - BCB-1 Alignment Marks

After proper exposure the samples are developed in DS-3000 at 35 degrees C for approximately 30 seconds. A few seconds into the process, the sample will start to change colors. Once the color changes stop, waiting approximately 3 more seconds ensures full development. The sample is then inserted into DS-3000 at room temperature for one minute while agitating with a pipette. The developer DS-3000 is removed and the sample dried by spinning for 120 seconds at 2000 RPM and blown with $N_2$. Once clean and dry the sample is baked on hot plate at 90 degrees C for 1 minute. Examining under a microscope, the BCB should be a consistent colorless film. Typically due to limits to which BCB may be resolved, the windows over the gold will actually have a thin film of BCB left on it which may be indicated by visible interference fringes. This window will be broken through completely in the next step. The fringes may be difficult to see since the gold reflection dominates over the thin BCB film interference in the window. Figure 15 shows the position of the BCB encapsulation area with respect to the waveguide.

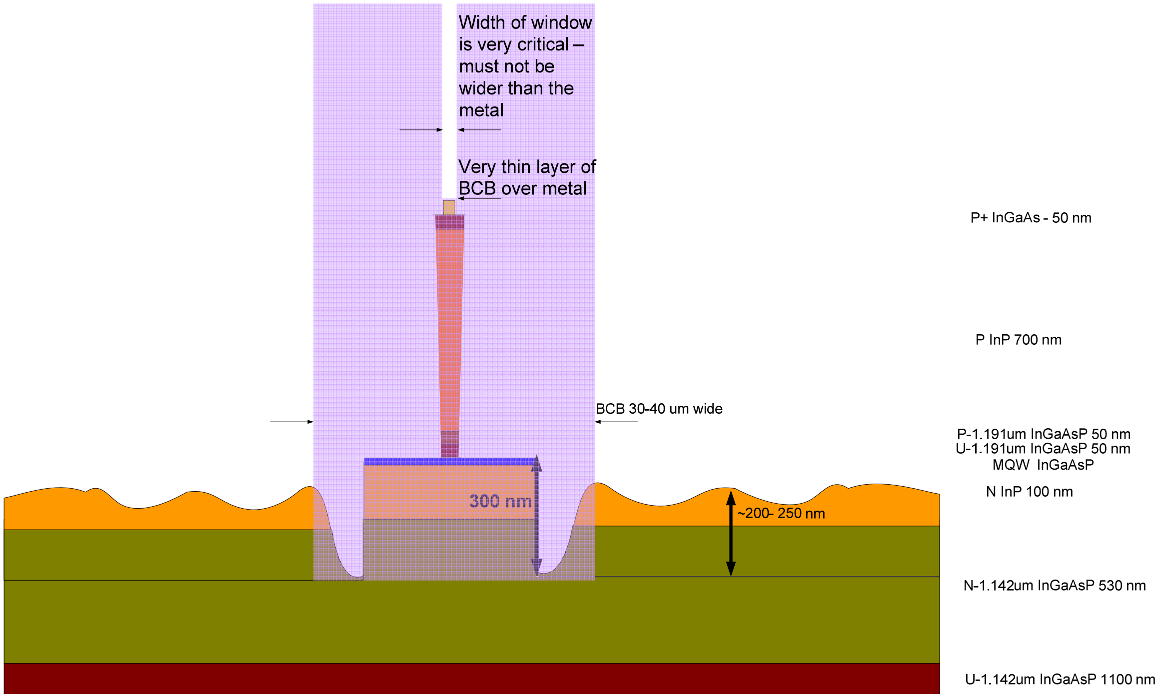

**Figure 15 - Proper BCB Alignment of Encapsulation on Device Structure**

## K. BCB Curing and Descum

The BCB layer must be cured in a RTA using a premixed $H_2$:$N_2$ (5%:95%) gas after allowing the chamber to purge for 15 minutes. The temperature ramps to an eventual 225 degrees C, but when 150 degrees C is reached the temperature needs to slowly ramp at a rate of 4-6 degrees C/min. The sample must dwell at 225 degrees C for 60 minutes. Only when the sample has cooled down should it be removed from chamber.

A descum procedure using the plasma asher follows the curing process and removes the BCB on the waveguide contact. This plasma cycle is used sparingly enough to open up the via but not long enough to affect BCB encapsulation. The etch is typically 100-300 nm of the BCB layer.

Two different gases are used to create an $O_2/CF_4$ mixture and is the only gas mixture that will etch the BCB layers. It is desirable to have premixed gas than to mix in the chamber because the etch rate is more consistent over time. Once the chamber is loaded with samples it must be purged with nitrogen several times to clear the chamber of any residue or water vapor. The sample is etched at 200 W for 2 minutes and verified with a microscope that the window or via is open.

If mixing gases in the chamber, the gas pressure ratios are 200 mT of $O_2$ and 40 mT of $CF_4$. If mixing in the chamber with the these gases has not been done for some time, weeks, the $CF_4$ lines needed to be cleared which is done by opening the $CF_4$ lines and allowing flow into the chamber. Then the flow into the chamber must be stopped and the $CF_4$ tank valve closed. The flow valve to the chamber should be opened and closed repeatedly until a negative pressure on the $CF_4$ regulator is read. This essentially cleans out the $CF_4$ line of any contaminates. The sample can be etched at 200 W for 2 minutes and verified with a microscope that the window or via is open.

## L. Negative Photoresist Application to Protect Gold Strip

This step is used to protect the p-metal on top of the mesa waveguide in the BCB opening from the final bretch step. NR9-3000P, 3 μm thick, photoresist is spun on the samples at 4000 RPM for 40 seconds, and they are baked on a hot plate at 150 degrees C for 70 seconds. The LOC Mask is used to align over the BCB encapsulation and is a very course alignment. The photoresist is used to protect the gold contact windows but the mask is much larger making this alignment less critical.

After exposure the samples are pre-develop baked at 100 degrees C for 70 seconds, cooled, developed in RD-6 for 30 seconds, rinsed with flowing DI water for 5 minutes, and blown dry. The developed photoresist is shown in Figure 16.

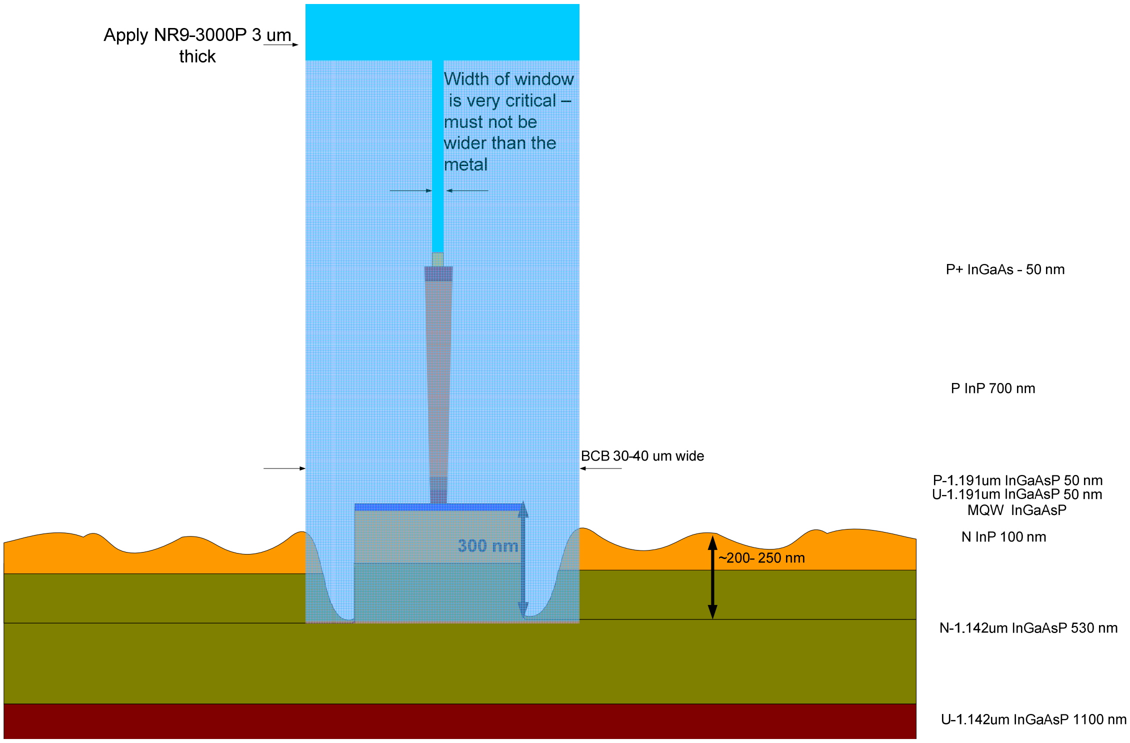

**Figure 16 - Photoresist Protection Layer on the Structure for the P-Metal Contact**

## M. Bretch

This bromine based etch removes the remaining n-InP layers and etches down into the n-InGaAsP layer. The etch should stop nearly half way, ~ 200-250 nm, into this layer. Using the $H_2O$:HBr:$Br_2$ (50 ml:10 ml:10 drops) solution the sample is etched for 60 seconds, rinsed in flowing DI water for 5 minutes, and blown dry with $N_2$. The photoresist is stripped off using the room temperature acetone, methanol and IPA rinse sequence followed by a rinse in flowing DI water for 30 minutes and blown dry with $N_2$. Figure 17 shows the approximate depth of the bretch.

The depth of this etch is important. If etched too far the area becomes too isolated from the electrical flow from the p-contact, and if not etched deep enough the area will remain semi-insulating and an n-contact will not be created. Using a profilometer to measure the entire structure, the etch depth can be calculated by subtraction of the after etch measurement from the before etch measurement. The etch should be approximately 200 nm into the InGaAsP layer, and it took to 50 seconds to give a 230 nm etch.

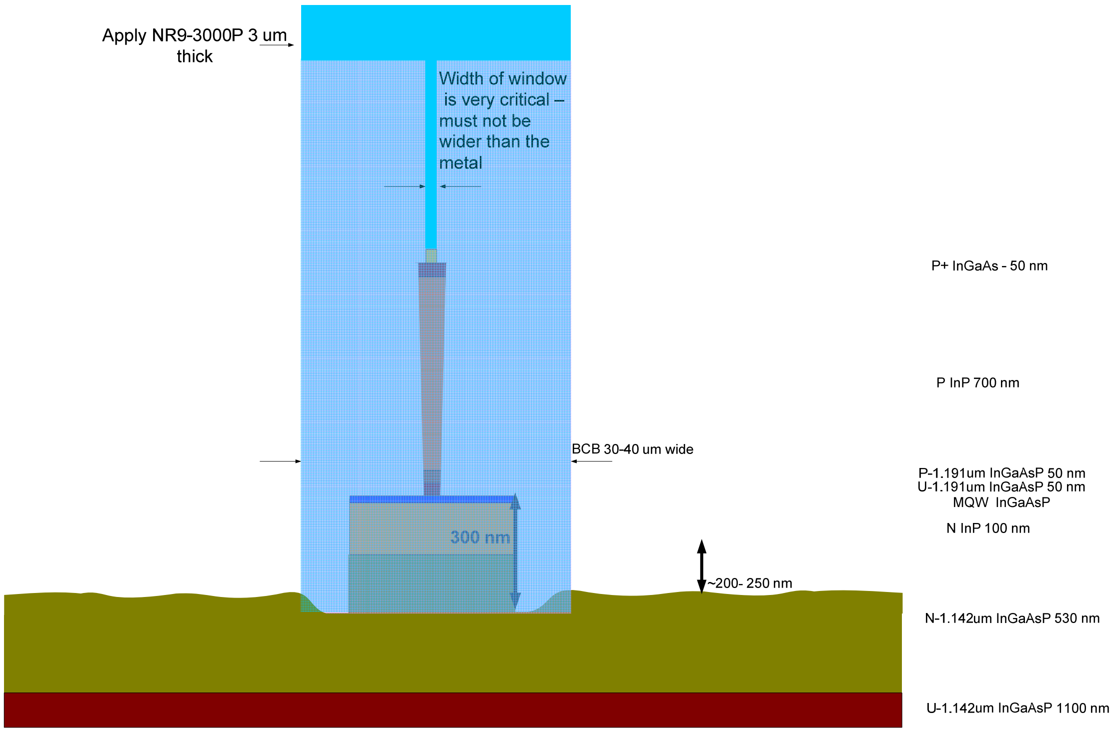

**Figure 17 – Final Bretch**

## N. Ground Pad Definition

This stage defines two ground pads on each side of the waveguide using Mask II-B. The 3 µm thick, negative photoresist NP9-3000P is spun on the samples at 4000 RPM for 40 seconds and baked on a hot plate at 150 degrees C for 70 seconds. The mask is aligned using the fiducial marks shown in Figure 18. The crosses were defined on the sample with a previous mask which aligns to the four squares on Mask II-B.

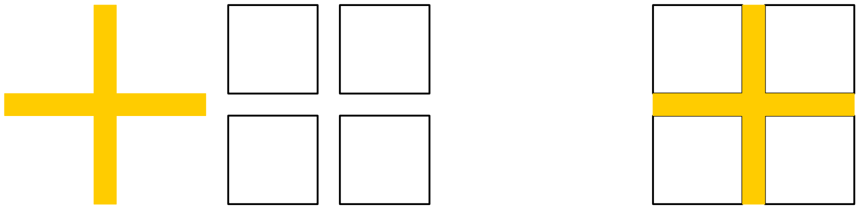

**Figure 18 - Alignment Fiducials for Defining Gold N-Contact Pads**

Figure 19 shows the photoresist pattern of Mask II-B. After exposure on the mask aligner, the sample is pre-develop baked at 100 degrees C for 70 seconds, cooled, and developed in RD-6 for 30 seconds. The sample is rinsed in flowing DI water for 5 minutes and blown dry with $N_2$. A

descum process in the plasma etcher follows with 200 mT of $O_2$ at 200W for 120 seconds. After development the clear areas define where the metal layers are to be deposited.
Because this sample sat for a few days without being processed, it must be stripped of any oxide that may have formed before metal deposition. Use a diluted BOE treatment using1:1 ratio of BOE and DI water. The sample should be dipped for 5 seconds. This is less harsh than the dip described in step A since that was starting with a fresh unprocessed wafer.

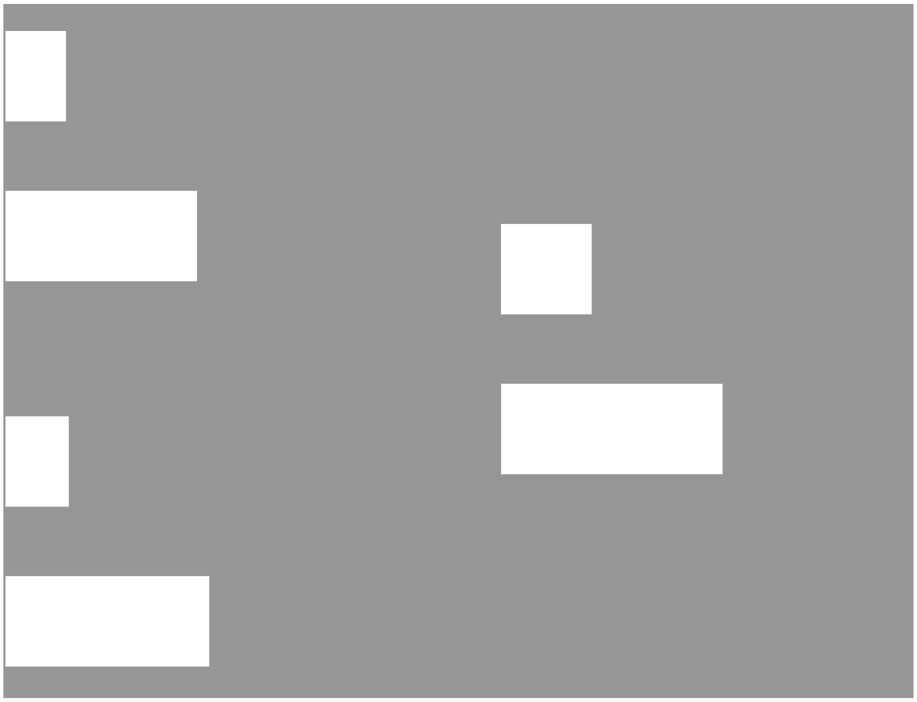

**Figure 19 - Mask II-B Ground Pads**

## O. N-Contact Metal Deposition

Metal is deposited using an e-beam evaporator with a metal sequence of Nickel/Germanium/Gold (Ni/Ge/Au) in a ratio of 100 nm/200 nm/2000 nm which will make a robust n-contact. Other common combinations such as NiGeAuNiAu can work as well. The choice of n-metal is less critical compared to the p-metal contact as long as low ohmic resistance and adequate adhesion is provided.

After deposition the photoresist is removed using an acetone soak at room temperature for 30 minutes while agitating to promote unwanted metal lift-off. Once lifted the sample is rinsed in room temperature methanol and IPA and blown dry with $N_2$. The cleaning is completed with a descum in the plasma asher with 200 mT of $O_2$ at 200 W for 120 seconds.

The metal layers must be turned into ohmic contacts and is achieved using the RTA. The chamber needs to purge using $N_2$ for 15 minutes to drive out any moisture. The samples are heated at 350 degrees C for 60 seconds in a forming gas environment of $H_2$:$N_2$, 5%:95%. The RTA needs to cool down before removing the devices. The sample should be examined under a microscope to look for damaged metal indicated by color changes and/or bubbling under or on the metal.

## P. BCB Bridge Build

A square area, 3.5 - 4 μm thick layer of BCB, is built in order to match the area height for the signal contacts pad to the height of the encapsulation BCB layer. The pattern from the BCB-2 mask used in this process step is shown in Figure 20. When the BCB-2 layer is finished, a signal contact pad will be deposited over this area to connect the p-metal waveguide electrode.

The adhesion assist layer AP-3000 is spun on at 3000 RPM for 30 seconds, and a second application may be needed if the BCB is not sticking to the surface. BCB is applied at 500 RPM for 10 seconds, 1000 RPM for 10 seconds, and 4000 RPM for 40 seconds, baked on hot plate at 90 degrees C for 3 minutes, and cooled.

The sample is aligned with the BCB-2 mask that was cleaned using a 15 minute soak in Primary Stripper A, generously rinsed with IPA, and blown dry with $N_2$.

After proper exposure the sample is developed in DS-3000 at 35 degrees C for approximately 30 seconds. A few seconds into the process, the sample will start to change colors. Once the color changes stop, waiting approximately 3 more seconds ensures full development. The sample is then inserted into DS-3000 at room temperature for one minute while agitating with a pipette. The developer is removed and the sample dried by spinning for 120 seconds at 2000 RPM and blown with $N_2$. Once clean and dry the sample is baked on hot plate at 90 degrees C for 1 minute.

Examining under a microscope, the BCB should be a consistent colorless film. The mask was aligned such that viewing from the top looking down at the waveguide, some overlap in the BCB-2 square and the BCB encapsulation layer would exist. Overlapping ensures that no gaps occur between the two BCB layers. A cross sectional schematic of the thick BCB-2 square layer is shown in Figure 21.

After verifying uniform BCB structures exist, the BCB needs to be cured and the sample descummed as defined in Section J.

**Figure 20 - BCB-2 Mask**

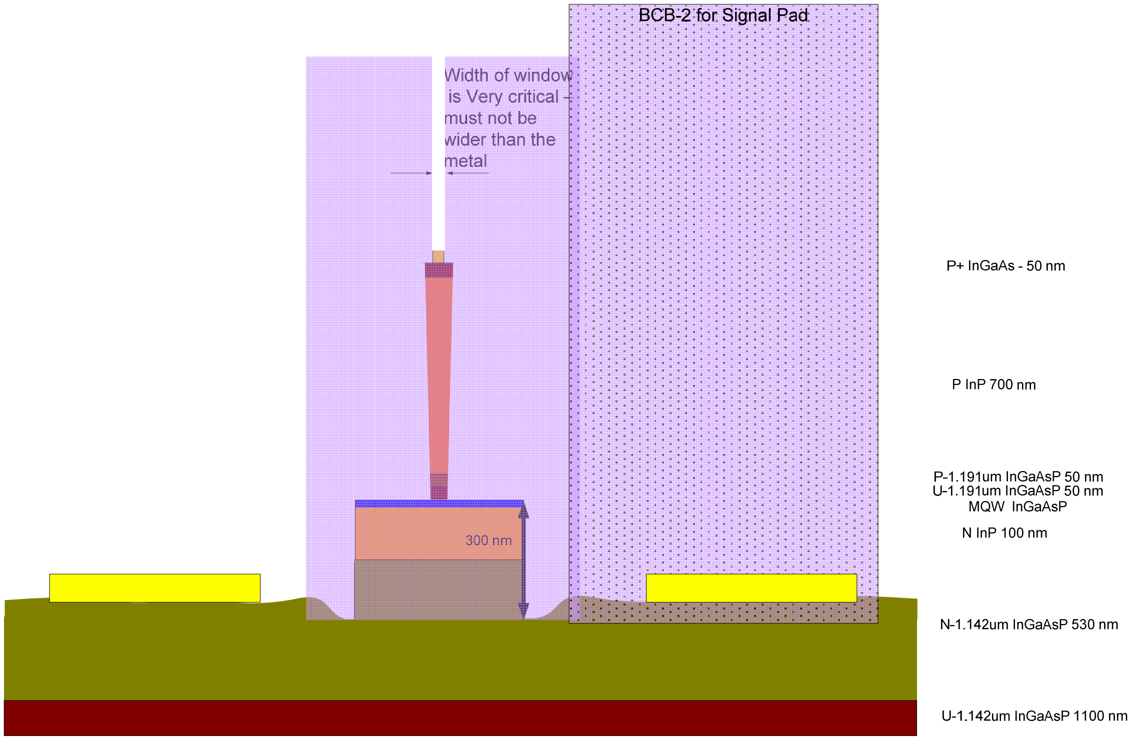

**Figure 21 - BCB Square Bridge for Signal Contact**

## Q. Metal Deposition on BCB Bridge for Signal Contact Pad

This procedure makes a gold signal pad on the BCB bridge and connects it to the p-metal contact on the waveguide and is defined using the Signal Pad Mask shown in Figure 22. The NP9-3000P, 3um thick, photoresist is spun onto the samples at 4000 RPM for 40 seconds and baked on a hot plate at 150 degrees C for 70 seconds. After properly cooling, the Signal Pad Mask is aligned and the samples exposed. A pre-develop bake is performed on a hot plate at 100 degrees C for 70 seconds. After cooling the photoresist is developed in RD-6 for 30 seconds, rinsed with flowing DI water for 5 minutes and dried with $N_2$.

The sample proceeds through a descum in the $O_2$ plasma asher with the controls set to 200 mT of $O_2$ at 200 W for 120 seconds. This will clean any of particles off the sample before the metallization layer is applied.

A metal seed layer using a sputter machine sequentially deposits Pd/Ti/Pd/Au:50 Å /100 Å/ 100 Å /1500 Å under high vacuum. This procedure should not be rushed. The metal combination for the signal pad provides much better adhesion compared to what a Au layer alone would exhibit. UCSD observed that gold alone or even e-beam deposited Ti/Au would not provide an appreciable level of adhesion needed for eventual probing and wire bonding.

After deposition the photoresist is removed using an acetone soak at room temperature for 30 minutes while agitating to promote unwanted metal lift-off. Once lifted the sample is rinsed in room temperature methanol and IPA and blown dry with $N_2$. The cleaning is completed with a descum in the plasma asher with 200 mT of $O_2$ at 200 W for 120 seconds.

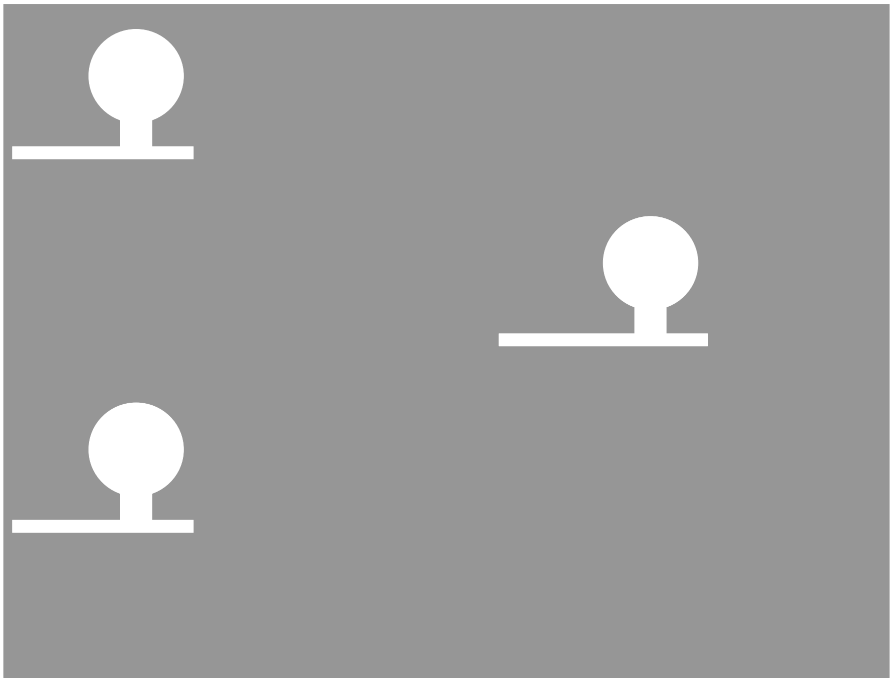

**Figure 22 - Signal Pad Mask**

## R. Gold Electroplating

A thick layer of Au needs to be electroplated onto the seeded contacts in order to make the ground and signal pads very robust for bonding or probing. The Au electroplated layer should be approximately 2-3 μm thick. Exact instructions to the electroplating process will not be detailed in this report. The system used at UCSD was a laboratory setup which has very operating steps unique to that system.

Prior to the electroplating 100 nm of Au must now be sputtered on the *entire* sample which acts as a solid seed layer giving the plating system a base of metal to which the thick Au will be deposited. The Au layer is sputtered in an Argon atmosphere of 35 sccm.

After 100 nm is deposited, the Au electroplating area is defined and patterned using the Ground and Signal Pad Mask shown in Figure 23. NR9-3000P, 3um thick, photoresist is spun onto the samples at 4000 RPM for 40 seconds and baked on hot plate at 150 degrees C for 70 seconds.

After properly cooling, the mask is aligned and the samples exposed. A pre-develop bake is performed on a hot plate at 100 degrees C for 70 seconds. After cooling the photoresist is developed in RD-6 for 30 seconds, rinsed with flowing DI water for 5 minutes and dried with $N_2$.

The sample proceeds through a descum in the plasma asher with the controls set to 200 mT of $O_2$ at 200 W for 120 seconds. This will clean any of particles off the sample before the metallization layer is applied.

With a Au plating system, 2-3 μm of Au is grown on the exposed areas which should provide the ground and signal pads to be sufficiently resilient for probing or wire bonding. The negative photoresist is stripped off using the room temperature acetone, methanol and IPA rinse sequence followed by a rinse in flowing DI water for 5 minutes and blown dry with $N_2$.

With the Au plating completed, the unwanted Au used for seeding must now be removed and is accomplished using the same Ground and Signal Pad mask but with a *positive* photoresist which protects the newly plated surface. The positive photoresist, S-1818, is spun onto the sample at 2500 RPM for 40 seconds baked on a on hot plate at 115 degrees C for 90 seconds. After cooling the Ground and Signal Pad mask is aligned and the samples are exposed. The photoresist is developed in MF-354 for 60 seconds, rinsed with flowing DI water for 5 minutes and dried with $N_2$. The sample should be examined under a microscope to verify the photoresist is properly developed and aligned well enough to protect the Au plating on the ground and signal pads.

The unwanted Au plating is etched from the sample for 30-60 seconds using a premixed solution of $KI/I_2$ gold etchant in a 1:1 ration with DI water. Careful examination of the sample is necessary to ensure all unwanted Au is dissolved, and additional etch time may be necessary. The sample is rinsed in flowing DI water and dried with $N_2$.

The photoresist is stripped off using the room temperature acetone, methanol and IPA rinse sequence followed by a rinse in flowing DI water for 5 minutes and blown dry with $N_2$. The sample should be examined to ensure all photoresist was removed.

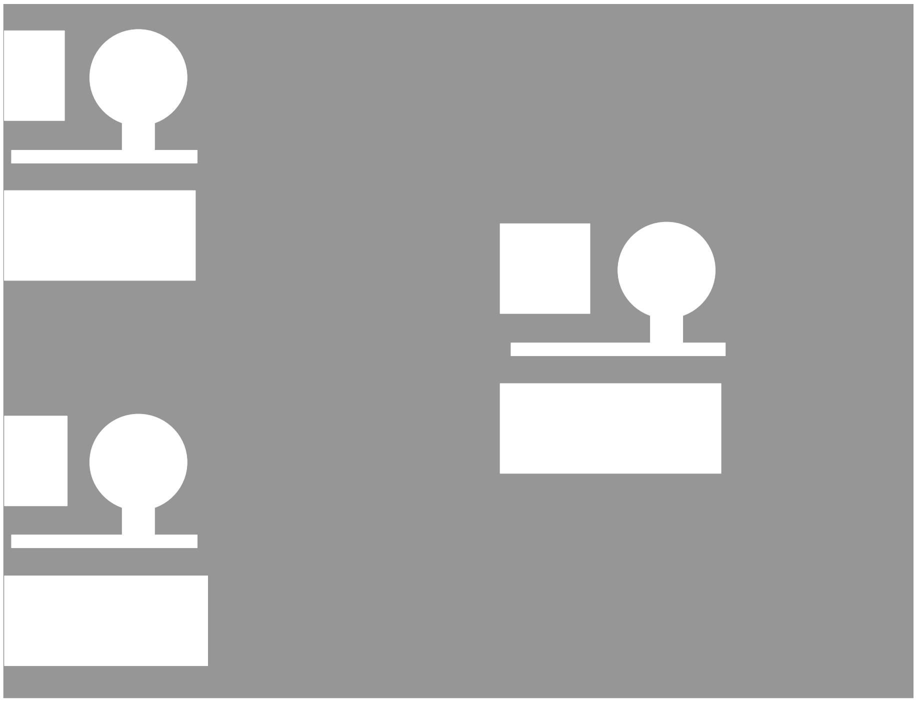

**Figure 23 - Ground and Signal Pad Mask for Electroplating**

## S. Substrate Thinning

The final step to the EAM fabrication is to thin the substrate. Thinning is necessary in order to cleave the samples. As InP material is very fragile, it is necessary to remove a portion of the substrate to relieve the stresses in order to provide consistent cleaves. The substrate is thinned down to 120-150 μm and depends on the device waveguide length, the shorter the thinner.

Thinning is accomplished using a polishing jig, black wax and a thickness gauge. The sample is measured with the gauge and its value used as a starting reference. The sample is attached to the polishing jig using heated black wax and positioned with the device side of the wafer in contact with the jig. The height gauge should be carefully placed next to the sample. Using the height characteristics of the wafer layer structure, the amount of substrate that needs to be removed can be calculated to obtain the 120-150 μm target thickness. A polishing slurry of 3 μm grit is used to start the removal of the substrate. Periodic measurement of the height of the polished sample monitors the removal. When the substrate is thinned to 160 μm, the slurry should change to 1 μm grit which will slow the removal of the substrate and create a good polished surface for the bottom of the substrate. The height is monitored until the required thickness is accomplished.

The sample can be removed from the black wax with some heat. Residual wax can be dissolved with acetone followed by a methanol and IPA rinse. The samples may be cleaved as needed. A final processed wafer will look like Figure 24.

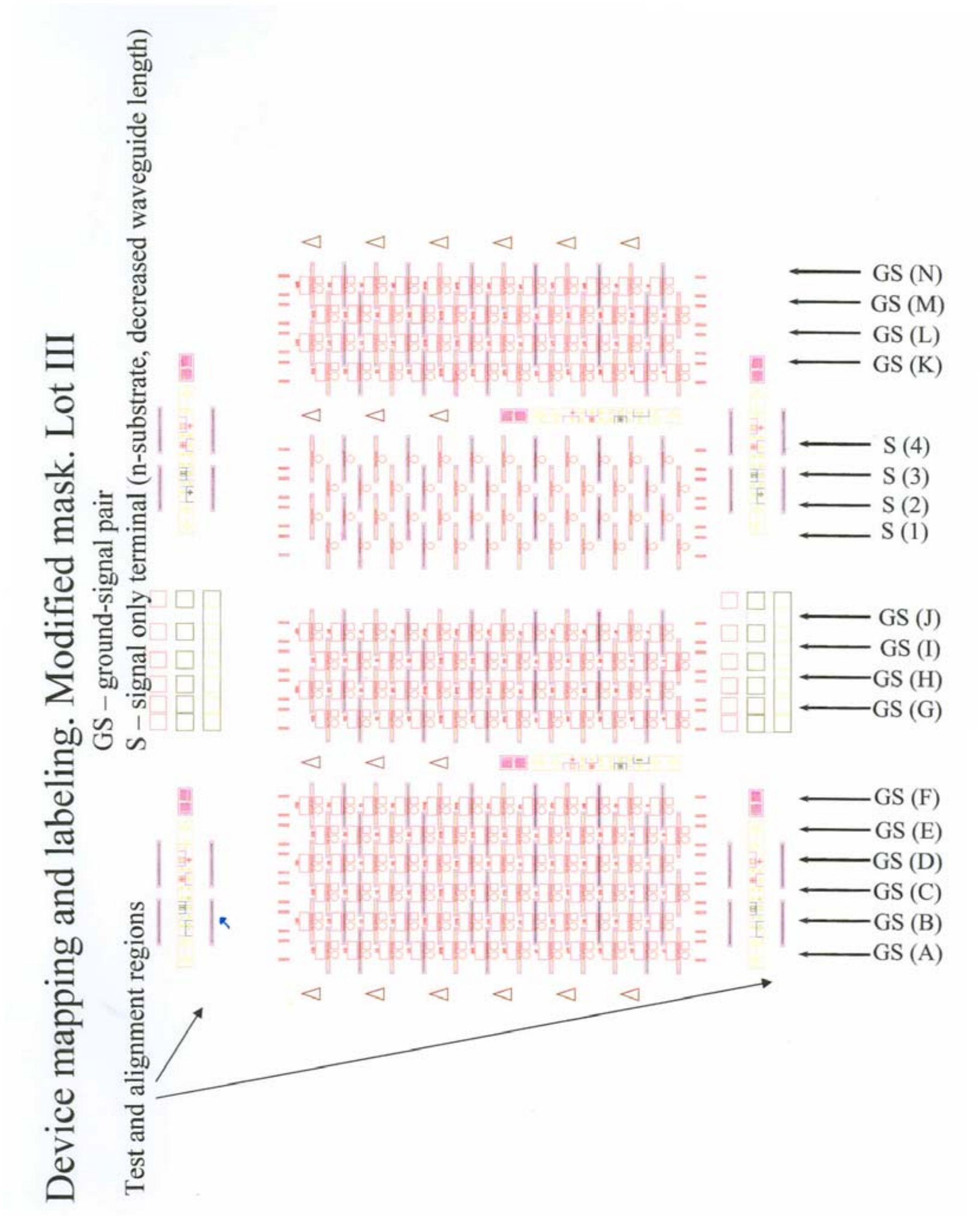

**Figure 24 - A Final Processed Wafer**

## **References**

1. Paul K. L. Yu, Yang Wu, G. L. Li, Yuling Zhuang, Phil Mages, A. R. Clawson, and W. X. Chen, “Semiconductor Photonic Components for RF Applications,” Final Technical Report: *AFRL-SN-RS-TR-2002-214*, August 2002.

2. P. K. L. Yu, Y. Wu, A. Chan, Y. Zhuang, J. Fischer, A. R. Clawson, I. Shubin, G. L. Li, and W. X. Chen, “Wideband Electroabsorption Modulator for Microwave Photonics,” Final Technical Report: *AFRL-SN-RS-TR-2004-281*, October 2004.

3. Paul K. L. Yu, “Wideband Electroabsorption Modulator for Microwave Photonics,” Final Technical Report: AFRL-SN-RS-TR-2005-408, December 2005.