Photolithography

Finding Optimal Exposure Time for NR21-20000P Photoresist

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I. Introduction

Photolithography is a micro-fabrication process utilized in the production of integrated circuits and micro-scale electronic components. Photoresist, a chemical that changes on the molecular level under UV radiation, is spun onto a silicon substrate. A glass mask with the desired chrome pattern on the glass surface is placed in proximity or in contact with the silicon substrate, and the substrate and photoresist are then exposed to UV radiation. The patterning on the mask inhibits radiation from reaching certain regions of the photoresist. Depending on the type of photoresist used, either only the blocked regions of photoresist or only the unblocked regions of photoresist remain after the exposure to UV radiation. A positive photoresist will develop away after being exposed to UV radiation while a negative photoresist will develop away when blocked from the exposure to UV radiation [1, Appendix A]. The mask is then removed, and the silicon substrate with the newly patterned photoresist is chemically etched, typically with buffered oxide etch (BOE) [1]. The BOE reacts with and deteriorates the exposed silicon oxide more quickly than the remaining photoresist. Therefore, the regions covered by photoresist do not deteriorate, while uncovered regions are etched away. The photoresist can then be chemically removed from the silicon substrate so that the silicon substrate is a three dimensional micro-scale projection of the patterned mask.

The fabrication of integrated circuits and of micro electric converters uses photolithographic processes to produce micro-scale components. Micro-scale inductors may use photolithography to form coils necessary to induce a magnetic field [2]. Inductors on these scales could be useful in LED lighting systems for the large inductance capability and low-volume for on-chip use [2]. Reference [2] shows how an inductor can be formed by encircling copper coils with a magnetic thin-film material. In reference [2], the dimensions of the inductor are 2.3 mm by 7.6 mm, with features smaller than 20 µm. The dimensions of the copper coils are critical in determining the power generated and lost due to defects in the inductor [2]. Accuracy in the formation of copper coils of optimal dimensions is necessary to minimize power loss. Negative Photoresist NR21-20000P and Resist Developer RD6 are used to form these copper coils. NR21-20000P is placed over the copper seed layer and exposed to form channels which the copper coils may be electroplated into.

According to the manufacturers, NR21-20000P and RD6 are compatible with 365 nm (I-line) UV radiation exposure [3]. NR21-20000P is sensitive to 46 mJ/cm^2 for a 1µm thick film [3]. The exposure time to decay NR21-20000P is dependent on the intensity of the radiation source and must be determined for the particular radiation source being used in conjunction with the NR21-20000P [3]. The radiation source used in the fabrication of the inductor in [2] is the *Karl Suss MJB3 UV400 Mask Aligner* [Appendix B]. Longer exposure times allow for small features to be patterned in the photoresist, and may also cause unwanted regions of the photoresist to be developed away [4]. Deviation from the optimal exposure time of the photoresist results in errors in feature resolution and sidewall profile. Research has been conducted in attempt to identify methods that will minimize critical dimension variation by varying factors such as exposure time and focus of the radiation source [4, 5]. Errors in resolution include: undercutting, enlarged features, or merged features. Undercutting is a phenomenon caused by UV radiation permeating to the base of regions covered by the mask so that the walls of the features are not perpendicular to the mask but rather angled inwards towards the features. Feature sizes may be larger than desired but have walls perpendicular to the mask if UV radiation diffracts between the silicon substrate and the covered regions of the mask. Features may also merge if uncovered regions are over exposed or over developed. Over exposure and over development may cause decay in the regions covered by photoresist and lead to enlarged features, effects that combine and result in merging. The minimum size achievable for IC components such as the inductor proposed in [2] is limited by the resolution of the photolithography for such thick features [5].

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In order to ensure optimal feature resolution and sidewall profiles in the micro-inductors in [2], we optimized the exposure time for NR21-20000P under 365 nm UV radiation with the *Karl Suss MJB3 UV400 Mask Aligner*. To determine the optimal exposure time for NR21-20000P, we exposed and analyzed six wafers with exposure times ranging from 50 seconds to 650 seconds. We chose this range of exposure times to investigate, because the micro-inductors in [2] were exposed to 365 nm UV radiation for approximately 350 seconds. Using the *MicroXAM-100 Interferometric Surface Profiler* and the *Jeol JSM-5310LV Scanning Electron Microscope* [Appendix B], we examined the feature size for all exposure times, and sidewall profiles for exposure times in the range of 300-375 seconds.

II. Procedure

We examined silicone samples spun with NR21-20000P, and exposed with 365nm I-line exposure. The purpose of our experiment was to determine an optimal exposure time for producing copper racetrack coil inductors using a mask provided by Thayer PhD student, Daniel Harburg. We determined this optimal exposure time by exposing quadrants of silicon wafers to a wide range of times ranging from 50 to 650 seconds and then examining the racetrack strips on the wafer in the SEM and the optical interference microscope. Following exposure and development, we cut the wafers to examine the accuracy of the profile, the height and straightness of the racetracks. There were two main results we were attempting to avoid in further continuation of the conductor development, which were identified with determined exposure times. If the sample is overexposed, light reflects and causes unwanted cross-linking to occur. This results in strips that are too wide, or not perfectly parallel sides. Too much cross-linking can also cause stress in the photoresist, which eventually causes cracking in the resist. Underexposure yields the opposite effect. The UV light would not cause enough cross-linking and the resulting strips are then too thin. Another effect of underexposure is that the photoresist on the bottom (the resist in contact with the wafer) is etched off by the developer, resulting in no strip at all. We are attempting to produce a sample with small, almost perfectly vertical and parallel strips where the copper coils are uniformly separated and do not merge in any place.

The recipe we used to make our samples with the NR21-20000P photoresist was:

1) Acetone, Isopropanol clean
2) 4 minute bake at 120°C to ensure that the sample is completely dry.
3) Cool for 10 min
4) Pour NR21-20000P photoresist and spin for 10 sec at 2500 RPM with 0.8 sec ramp

(This time and speed was chosen based on the information in the datasheet to obtain a film thickness of 50,000 nm. We used the Specialty Coating Systems G3-8 Spinner.)

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5) Let sit 10 min to even the height of the film. NR21-20000P is very viscous and after spinning the film thicker on the outer edge of the wafer.
6) Soft-bake at 80°C for 6 min and then 150°C for 2 min in order to semi-harden the photoresist and improve the adhesion of the resist to the wafer.
7) Let cool for 15 min
8) Expose wafer

   We exposed the wafers using the Karl Suss MJB3 UV400 Mask Aligner. We exposed each quadrant for a different amount of time by exposing the whole wafer, followed by the right half of the wafer, followed by the bottom half of the wafer. For example, to expose quadrants for a 50-200 second range, we exposed the whole wafer for 50 seconds, the right half for 50 seconds, then the bottom half for 100 seconds. This exposing method minimized the amount of accidental exposure from light scattering.

   The exposure times ranging from 50-650 seconds were chosen based on literature from the authors of Reference [2], which indicated that the Karl Suss MJB3 UV400 Mask Aligner had a light source intensity such that NR21-20000P photoresist was likely to develop somewhere in this time range. According to the datasheet, the photoresist should be exposed to 46 mJ/cm^2 for a 1µm thick film. However, the sensor to calculate the power from the mask aligner was broken which added to the need for a wide range of experimental exposure times.

9) Post bake for 5 minutes at 80°, per the instructions on the data sheet.
10) Let cool for 15 min
11) Develop for 3:30 with RD6 resist developer to remove any photoresist not exposed to UV light.

To examine the racetracks, we looked at a top down view using both the MicroXAM-100 Interferometric Surface Profiler [Appendix B] and the Joel JSM-5310LV Scanning Electron Microscope [Appendix B]. Profile examination was done by both cleaving the wafers, as well as cutting strips with the Dicing Saw.

We cleaved the first trial of wafers, and used the dicing saw for the next two trials in order to obtain a cleaner cut for more accurate profile examination. The cleaved wafers appeared to be (111), instead of the (100) wafers we had predicted them to be. This plane difference caused the break to occur at on angle to the wafer flat and the long edge of the racetracks, instead of cutting perpendicular to the them. The second trial wafers were cut in the saw at a speed of 5mm/min, and the third trial wafers were cut at 15mm/min, in an attempt to minimize the stress induced on the wafer by the cutting process. During the cutting process, which took about 1.5 hours, the wafer is under a constant water flow. The resist on our second trial wafers (the first wafers cut in the saw) began to flake less than 24 hours after removal from the saw. We initially hypothesized that the constant water flow negatively affected the resist, which caused the phenomenon of flaking. In order to determine whether or not this hypothesis was sound, we exposed a whole wafer

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at 300 seconds, and then soaked it in water for two hours. This wafer was then compared to the other wafer exposed at 300 seconds in the same trial.

One major source of measurement error was the inconsistency in methods for examining the racetrack profiles. The different imaging devices did not allow for accurate data comparison of each wafer and exposure time. Another error occurred when we tried cleaving, as we thought we had a (100) wafer when it was actually a (111) wafer. The dicing saw caused a large amount of stress on the wafer and photoresist, eventually causing the photoresist to crack. A third issue we encountered over the course of experimentation was that the NR21-20000P dries out and begins to crack if it is left out for a couple of days. If this cracking occurred before we imaged the wafers, we were then observing a skewed set of images and data. Despite these issues with the imaging and cutting, our data should be reproducible because the procedure for producing the racetracks on the silicon wafers was kept very controlled and we observed the general hypothesized trends with under and over exposure.

III. Results and Discussion

We found that the optimum exposure time for the racetrack pattern to be between 300 seconds and 375 seconds. While investigating the various exposure times, we encountered various undesirable effects. For exposure times that were less than 300 seconds, we observed that not enough cross-linking occurred in the resist, and features were consequently lost when the wafer was developed. For exposure times greater than 375 seconds, features were also lost, due to the occurrences of undercutting and merging.

Exposure of a negative photoresist causes cross-links to be formed, meaning that the exposed areas will not be dissolved when placed in developer. At low exposure times, a minimal amount of cross-linking occurred, which resulted in non-vertical racetrack walls and cross-links that did not form all the way down to the silicon wafer – causing flakes of exposed photoresist to form on top of an unexposed layer. These occurrences resulted in lost racetrack features, as the underexposure further caused features to be smaller than expected, or entirely absent. We found that as exposure time approached 50 seconds, the more severe the above problems became.

For the higher exposure times, we lost features due to undercutting. When the wafer is overexposed, the UV radiation has a chance to diffract under the mask, meaning that some regions of photoresist become cross-linked, despite being covered by the mask. This causes the walls of the features to be slanted, and in some cases caused the features to merge. These weakened feature walls were also affected by the strain of shrinking the photoresist layer. The thin walls allowed the features to be easily interrupted by cracks that formed due to the strain on the photoresist. This caused some pieces of photoresist to crack off entirely, especially in the high detail of the racetracks. We found that as exposure time approached 650 seconds, the occurrence of excessive cross-linking increased.

Over the course of our testing and analysis, we determined that the optimal exposure time was in the range of 300-375 seconds. Due to several malfunctions with the SEM and X-Ray Interference machine, we were unable to image all of the wafers in both devices, but we were able to see drastic effects after both over and under exposure times. If allowed further time, we would obtain more profile images of the wafers to determine

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the accuracy of the sidewalls. The only exposure times that produced a generally uniform height in the racetracks occurred in the 300-375 second range.

After initially observing cracking and signs of stress on the silicon wafer after sawing, and testing this as a possibly being caused by exposure to water, it was concluded that cracking was a result of the stress induced by the dicing saw. This, however, will not adversely affect the ultimate use of the racetracks, as they will not be cut until after the resist has been removed from the wafer.

This flaking of the photoresist affected imaging, as an accurate height of the photoresist was unable to be obtained, and the top-down images in the X-Ray diffraction machine appeared very "spongey." If continuing this project, we would further investigate the stress and flaking phenomenon with a Guckel Ring. A Guckel ring is a structure composed of a ring with a crossbeam inside [Appendix D] and is often co-fabricated to the wafer. The Guckel ring allows one to make stress and strain measurements, as the release of structure under tensile stress causes the ring to contract and the crossbeam to compress. The critical load of the wafer is reached when the Guckel ring crossbeam buckles, which is detected and seen with an optical microscope and profilometer to calculate the tensile stress. This device can be used to estimate a few parameters, such as: strain gradient, residual strain, and certain material properties. In order to confirm the possibility of the saw, and overexposure causing too much stress on the rings, we would use the Guckel ring to observe the effects of each of these steps in order to better understand any sources of error.

With the Guckel ring, we would have been able to gain a quantitative analysis of stress on wafers that had both high and low exposure time.

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Reference [2] indicates that the optimal height for each racetrack would be 50 µm. We used the X-Ray interference machine to generate line profile views [Appendix C] of the wafer exposed at 300, 325, 350 and 375s. The 300s exposure racetracks were 42 µm tall and approximately 100 µm wide. The 325s exposure racetracks were 40.6 µm tall and 115 µm wide. The 350s exposure racetracks were 40.1 µm tall and 125 µm wide. The 375s exposure racetracks were 40.1 µm tall and approximately 130 µm wide. This data is consistent with the idea that as exposure time increases, the width of the features increases. While a bit under the optimal ractrack height, we observed a uniformity in sidewalls that was not seen outside of the 300-375 second rage. We were not able to determine major differences in feature sizes with the SEM images, as the scale was too large.

In conclusion, we suggest that further research be conducted on wafers exposed to time between 300 seconds and 375 seconds. While not able to provide an exact optimal time, this study offers clear data and images that exposure times outside of this range results in unwanted effects to the racetrack walls. Further continuation of this project should include a stress and strain analysis of the wafer and corresponding exposure times, as well as a more comprehensive observational study of the sidewall profiles.

Appendix A: Diagrams of errors due to underexposure and overexposure of photoresists to radiation

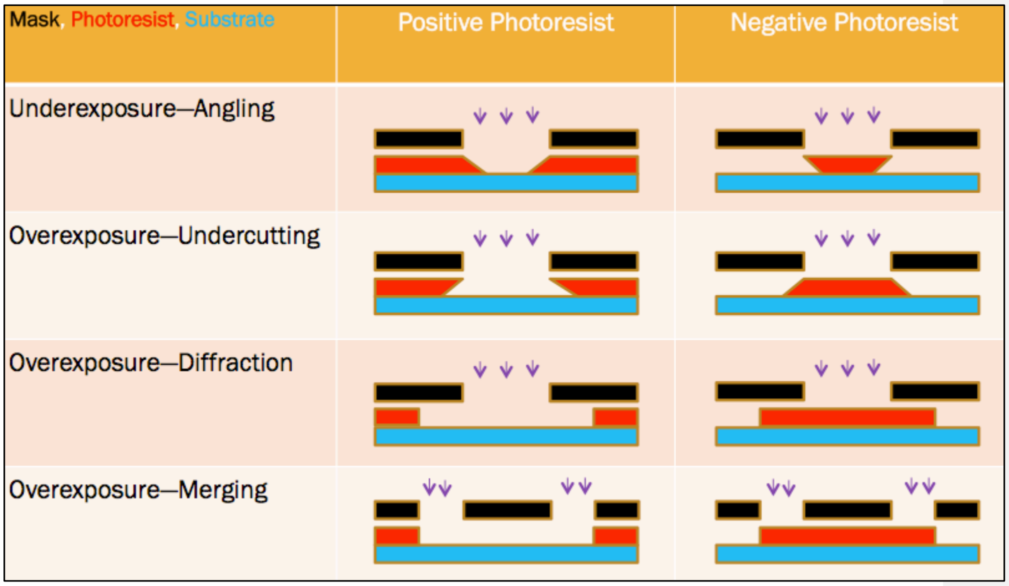

Figure 1. Table of the effects of deviation from the optimal exposure time in both positive and negative photoresists

Appendix B: Equipment used in processing and analysis

Figure 1. Specialty Coating Systems G3-8 Spinner

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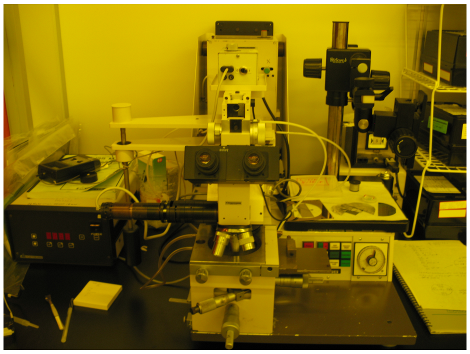

Figure 2. Karl Suss MJB3 UV400 Mask Aligner

Figure 3. MicroXAM-100 Interferometric Surface Profiler

Figure 4. Hummer 6.2 Sputterer

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Figure 5. Jeol JSM-5310LV Scanning Electron Microscope

Appendix C: Line-profile images of racetrack cross-sections

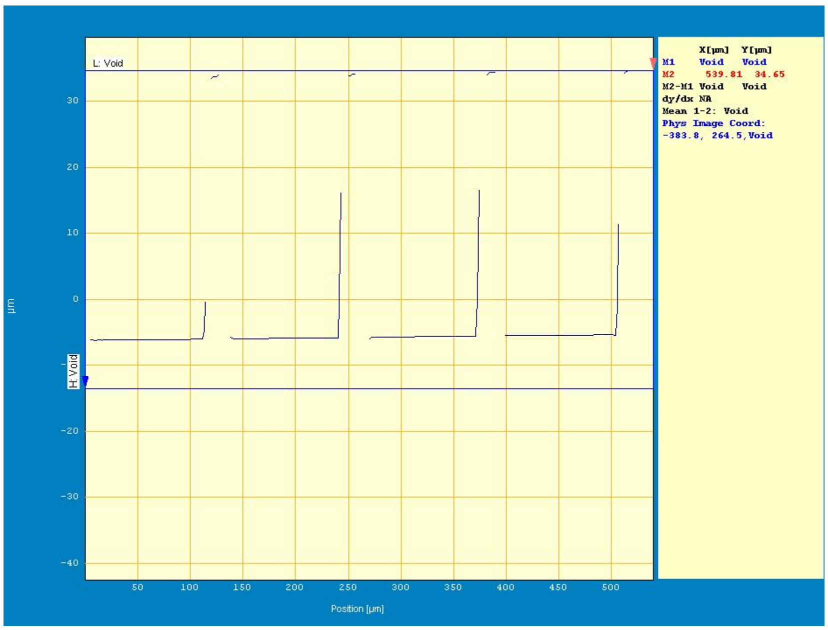

Figure 1. Line-profile of 300 sec exposure.

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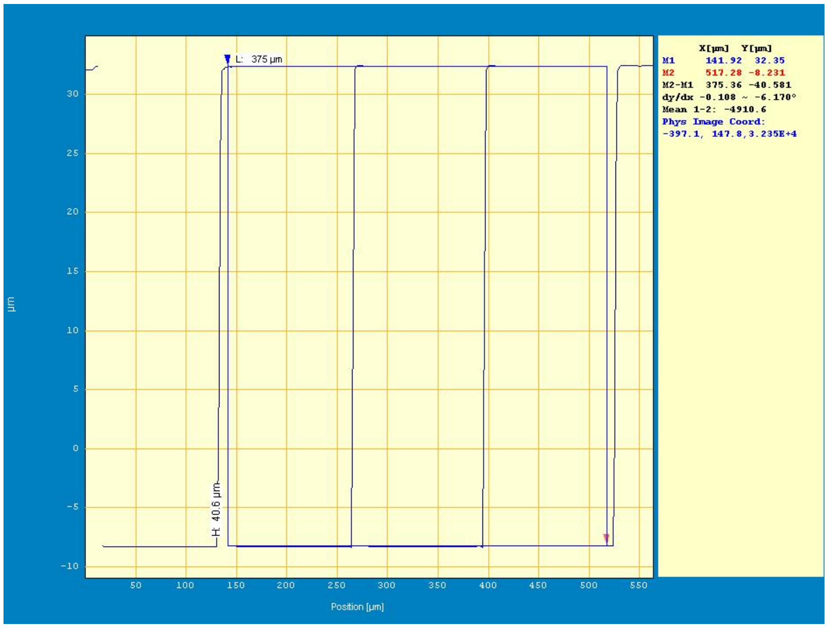

Figure 2. Line-profile of 325 sec exposure

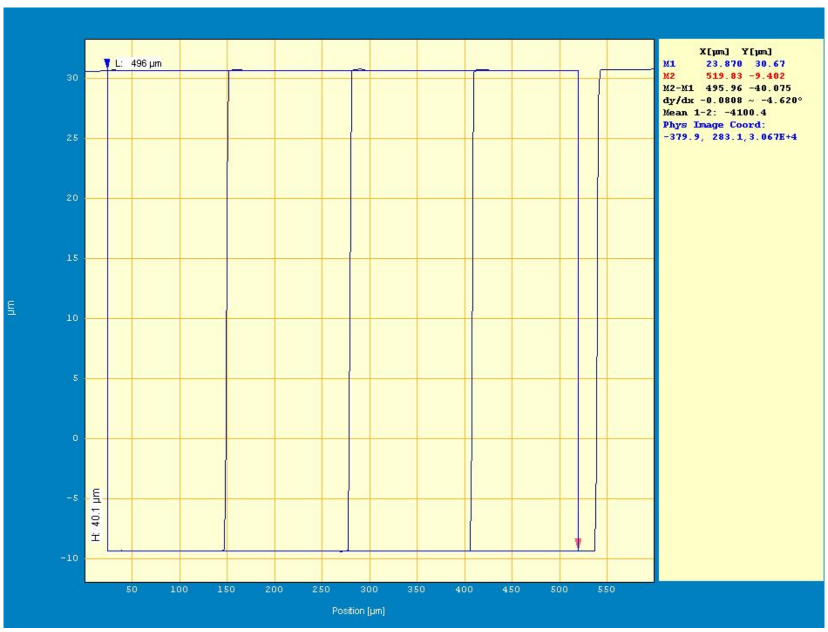

Figure 3. Line-profile of 350 sec exposure.

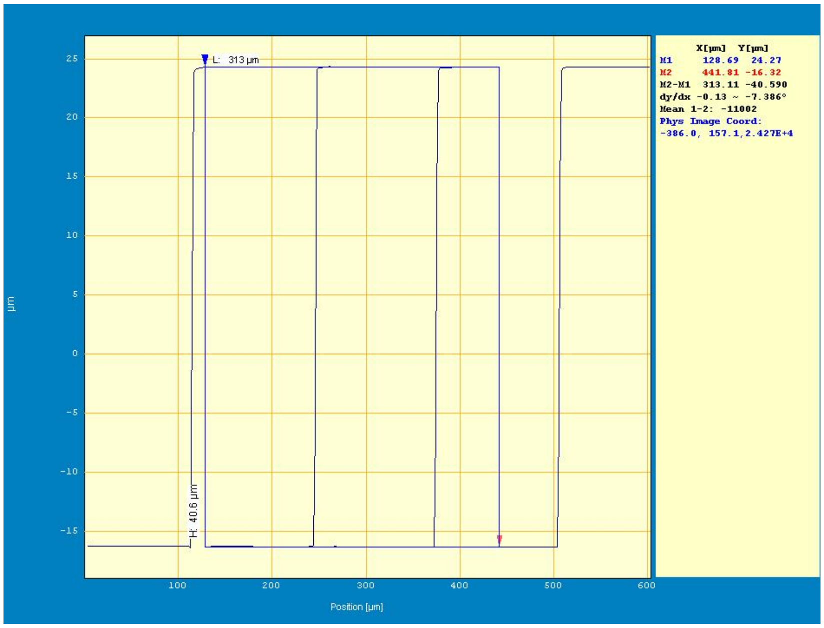

Figure 4. Line-profile of 375 sec exposure.

Appendix D: Guckel Ring

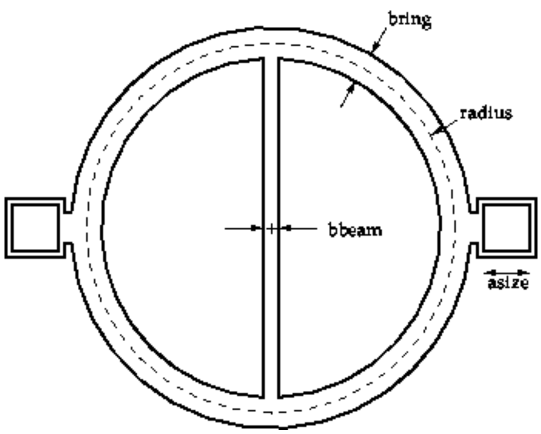

Figure 1. Illustration of a guckel ring. [6]

References

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