# A Design of Experiments Approach to BCB Etch Uniformity Improvements

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## Abstract

Nortel Networks GaInP/GaAs HBT process[1,2] employs a bisbenzocyclobutene (BCB) intermetal dielectric, chosen for it's excellent planarization and dielectric properties. During a 3" to 4" conversion of the GaAs HBT production facility, the existing 3" etch conditions for the BCB etch using $CF_4/O_2$ in an Ar carrier gas were found to produce inadequate uniformity control on the 4" wafers. A program was initiated to improve etch uniformity using a Design of Experiments (DOE) methodology. Since there was already a strong starting point for the experiments (the etch conditions used in the 3" process), the approach was to use a response surface method (RSM) to optimize the existing 3" conditions for 4" wafers, forgoing the screening type experiments that would normally be required for a new process. As a result of the experiments, etch uniformity improved from ~14% to ~6%.

## Introduction

Designed experiments have long been a staple of semiconductor manufacturing, where tight process tolerances dictate that processes with the widest possible margins are employed. There are many good introductory and advanced texts[3, 4] on experimental design which provide good background on the Design Of Experiments (DOE) methodology. Commercially available experimental design software[5,6] makes producing and analyzing a designed experiment, which is computationally intensive when done by hand, fairly straight forward. If the starting point for experimental investigations is not well known, i.e. introducing a new process, then an experimental series which begins with 'screening' style experiments is most often recommended[7]. Screening experiments typically provide information about first order (linear) interactions amongst experimental variables with some second order (variable to variable interactions) depending on the choice of experiment. Screening experiments are typically used to provide a starting point for further experimentation. If a strong starting point already exists, a more in-depth exploration of the experimental space can be obtained using a Response Surface Method (RSM) experiment. The advantage of using an RSM style experiment is that it allows the experimenter to generate a quadratic (or higher) model of a surface in the explored experimental space and, within the limits of that surface, determine optimum process conditions.

## Background

The initial etch conditions were taken from the existing 3" process, established when the BCB intermetal dielectric process was introduced into the Nortel Networks HBT manufacturing facility in 1992. At that time a series of screening experiments was performed to determine etch conditions that produced good results for three inch wafers in a Tegal 901-e, 6 inch capable tool. The gas composition, RF forward power, pressure were all examined with respect to their impact on standard etch parameters such as etch rate, cross wafer uniformity, surface roughness, selectivity to the underlying SiON, etc. Table 1 shows the process conditions determined for the 3" wafers and carried over to the 4".

When the change to 4" wafers was made, it was found that the etch uniformity had changed from ~8% to ~14% due to a dramatic increase in the amount of BCB removed from the edges of the 4" wafers. Since changing the RF forward power and/or pressure can in some cases substantially change the characteristic etch shape (bowl or dome), it was felt that a RSM style experiment with those parameters would provide a better set of etch conditions for the 4" substrates.

**Experimental Design**

There are many styles of response surface designs to chose from when designing an experiment, each of which has its own particular merits. Box-Behnken and Central Composite are two examples of designs which can be used to generate non-linear models of a given experimental region.. In this optimization, a Central Composite in a Cube (CCC) design was chosen as the experimental design. The reasons for this choice were several: the CCC design provides good experimental efficiencies; for the number of experimental factors chosen for study (2), the CCC design offered a reasonable number of experimental runs; and, the CCC design is particularly easy to implement on a piece of process equipment since the factor settings are either –1,0,1 when coded (i.e. the corners of the experimental space).

**Experiment Results**

The process region chosen for study was centered around the existing etch conditions and, having selected the initial variables for study, (RF Forward Power – RFP and chamber Pressures – PRESS), the ECHIP program was used to generate the experiment. The experimental design in the variables RFP and PRESS is shown in Table 2. This design has 15 runs, 9 of which are unique, 6 of which are replicates of the center point. The run order in the experiment is randomized as per normal DOE practice to spread the influence of variables not explicitly included in the design over all of the runs.[8] The response of the uniformity (defined as RANGE/(2*AVG)) as modeled is shown in Figure 1. As can be seen from the plot, the process conditions explored indicated that the existing conditions were near optimum with respect to PRESS and RFP. However, significant lack of fit was detected in the experiment, indicating (as had been observed) that the current conditions of RF power, pressure, did not provide consistent and repeatable etching of the BCB film on 100mm substrates.

In light of the lack of potential improvement available in the explored experimental space, a careful re-examination of the original screening experiments was conducted to try and determine other possible etch conditions which would yield improved uniformity. As a result of this re-examination, the $CF_4$:$O_2$ ratio in the etch was adjusted to 2.15:1 from the existing 0.58:1, this ratio having been shown in the one of the screening experiments to produce better uniformity, although there was an increase in the surface roughness. A second RSM experiment in RFP and PRESS was designed around reduced values of both (again taken from the earlier screening experiments). The 2$^{nd}$ experiment design is shown in Table 3. The results of this series of experiments is shown in Figure 2. The uniformity response in this series has a local minima of ~4.8% with an estimated replicate standard deviation of 1.25%, at RFP = 190 Watts and PRESS = 310 mTorr, close to 10% better then the existing etch conditions. Additionally, the experimental results showed no lack of fit, indicating that the etch conditions in this regime were stable and repeatable. To test the stability and repeatability of the newly indicated process conditions, 3 wafers were run through under the new conditions. The results of this brief experiment are shown in Figure 3. These results were consistent with the variability estimated in the designed experiment and while certainly not providing statistical certainty, they did offer reassurance that the proposed etch conditions were acceptable. It was found however, on examination of the BCB surface after etch, that the edges of the wafers (within ~4mm of the edge) had a slight haze, visible in a dark box. SEM examination of the haze showed a slight roughening of the surface at the edges. the effect of this roughening was to make ME2 Au appear dark. While this problem was mostly of a cosmetic nature, a short etch at higher pressure in $CF_4/O_2$ without the Ar was added to eliminate it. This resulted in an acceptable surface, without materially affecting the uniformity.

## Conclusions

Screening experiments, performed when BCB was introduced to Nortel's HBT process were expanded on by generating RSM experiments. These RSM experiments, 2 of which were performed, in turn identified BCB etch process conditions which improved uniformity form ~14% to ~6% cross wafer. These experiments were quick to perform (taking less then 1 day each to perform and analyze after substrate preparation) and provided clear direction in establishing local optimum process conditions. Design Of Experiments methods are powerful tools in the process engineers toolbox and should are useful whenever process optimization is done.


## Acknowledgements

The author would like to thank the operational staff of the Nortel Networks HBT manufacturing facility for processing assistance and more importantly, for their tolerance.


**Table 1**

BCB Etch Initial Conditions

| Variable | Valu | Units |
|---|---|---|
| **RF** | 200 | Watts |
| **Pressure** | 500 | mTorr |
| **Ar** | 53 | SCC |
| **$O_2$** | 36 | SCC |
| **$CF_4$** | 21 | SCC |

**Table 2**

Initial CCC Experiment Design

| Run No. | Pressure (mTorr) | Power (Watts) | Run No. | Pressure (mTorr) | Power (Watts) |
|---|---|---|---|---|---|
| 6 | 400 | 300 | 9 | 500 | 200 |
| 3 | 500 | 100 | 9 | 500 | 200 |
| 2 | 600 | 200 | 4 | 500 | 300 |
| 9 | 500 | 200 | 9 | 500 | 200 |
| 8 | 400 | 100 | 5 | 600 | 300 |
| 7 | 600 | 100 | 9 | 500 | 200 |
| 9 | 500 | 200 | 9 | 500 | 200 |
| 1 | 400 | 200 | | | |

**Table 3**

2nd CCC Experiment Design

| Run No. | Pressure (mTorr) | Power (Watts) | Run No. | Pressure (mTorr) | Power (Watts) |
|---|---|---|---|---|---|
| 3 | 150 | 325 | 1 | 200 | 375 |
| 6 | 250 | 325 | 2 | 150 | 375 |
| 8 | 150 | 275 | 1 | 200 | 375 |
| 5 | 200 | 275 | 2 | 150 | 375 |
| 9 | 250 | 275 | 10 | 250 | 375 |
| 3 | 150 | 325 | 4 | 200 | 325 |
| 10 | 250 | 375 | 2 | 150 | 375 |

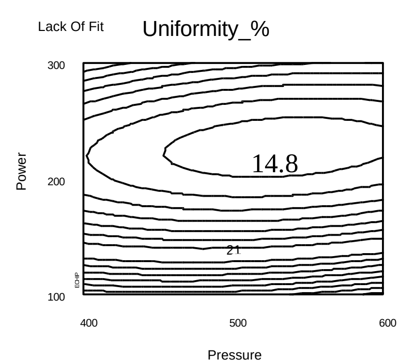


**Figure 1: Initial Experiment Etch Uniformity**

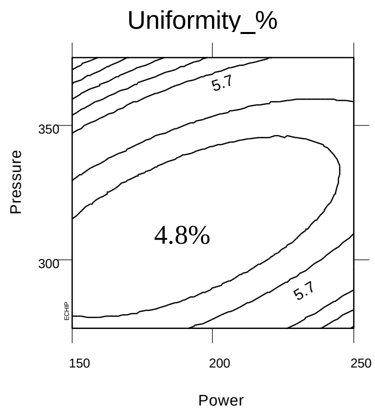


**Figure 2: 2nd CCC Experiment etch Uniformity**

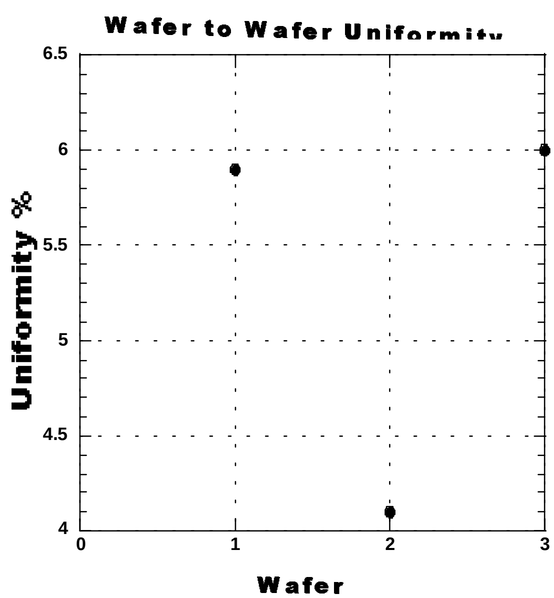


**Figure 3: Etch Repeatability**

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