Probes for Monitoring Low Dose Silicon Ion Implants for Process Yield Enhancement

Daniel H. Rosenblatt
Samsung Microwave Semiconductor
1530 McCarthy Boulevard
Milpitas, CA 95035
408-433-2222

ABSTRACT
A newly developed optical densitometry probe, and existing thermal wave, eddy current sheet resistance, and four-point GaAs sheet resistance probes were used to measure low dose Si+ ion implants. The four probes were evaluated for their ability to detect implant dose uniformity, their sensitivity to low doses, and their repeatability for multiple measurements on a single wafer, and on several wafers implanted with the same dose. The new optical densitometry probe was found to be highly sensitive \((S = 0.5 - 0.6)\) to low doses \((\text{Si}^+, 100 \text{ keV}, 0.75E12 - 5E12 \text{ cm}^{-2}\)) \text{.} The thermal wave probe was found to be relatively insensitive \((S = 0.1 - 0.15)\) in the same low dose region \((\text{Si}^+, 100 \text{ keV}, 2E12 - 4E12)\) and moderately sensitive \((S = 0.40)\) at higher doses \((\text{Si}^+, 150 \text{ keV}, 6E13 - 9E13)\). The eddy current sheet resistance probe was found to be about four times more precise as the GaAs four point probe. By providing precise information about low Si+ dose uniformity, all four techniques can be applied to yield improvement of GaAs devices made with ion implantation.

INTRODUCTION
One of the key factors in yield enhancement of GaAs ICs made on ion implanted active layers is the ability to monitor the dose uniformity across a wafer and the dose repeatability from wafer to wafer of the ion implanted layer. Many techniques used to monitor B+, P+, and As+ implants used in Si device applications (e.g., photoresist-based optical densitometry, C-V profiling, and DC four point probing) have lacked the sensitivity and repeatability to monitor low dose Si+ implants used in GaAs device applications. The purpose of this work is to explore four probes which are particularly suitable for GaAs manufacturing technology. Each probe can detect low Si+ doses and assure that the uniformity of implants is sufficient to obtain high device yields.

The optical densitometry and thermal wave techniques directly monitor the implant and do not require an anneal of the substrate being implanted. The eddy current sheet resistance and GaAs four point sheet resistance techniques require an anneal of a GaAs substrate after the ion implant and are therefore indirect measurements. Indirect monitors are more prone to inaccuracies introduced by the non-uniformities inherent in GaAs substrates and annealing processes.

EXPERIMENTAL DETAILS
\(^{28}\text{Si}^+\) and \(^{29}\text{Si}^+\) implants were done on an Eaton 200 MCA ion implanter at Samsung Microwave and on a Veeco 2400MP implanter at IICO Corp., respectively. The tilt and twist angles were 10 and 20 degrees, respectively, to minimize ion channeling. For the optical densitometry study, polymer coated glass substrates were used. For the thermal wave study, Si\{100\} substrates were used. For the sheet resistance studies, semi-insulating GaAs \{100\} substrates were used. The implanted GaAs substrates were furnace annealed in an arsine ambient for 40 minutes at 850 degrees C.

A NEW OPTICAL DENSITOMETRY PROBE
Until recently, the most advanced optical densitometry technique to monitor dose used photoresist coated glass wafers. These wafers are light sensitive, have short shelf-life, exhibit serious relaxation after implant, and are relatively insensitive at doses below \(1E14\). In this paper, measurements of Si+ implants by a newly developed instrument (which is now commercially available) are presented for the first time. In order to read doses in the \(1E11 - 1E13\) region with this new instrument, a dye impregnated transparent polymer film has been developed that changes its optical density when implanted. The polymer film is applied to a recyclable glass wafer, which is then implanted. Optical density is measured at about 350 sites on a 3" diameter wafer. The mean number of optical density counts, and the one sigma standard deviation of those counts are then calculated.

Figure 1 shows a map of the across-wafer uniformity for a 100 keV, \(3E12\), \(^{29}\text{Si}^+\) implant using this technique. The standard deviation for
the implant is indicative of the uniformity of the implant itself, and not convolved with the effects of the GaAs substrate, the anneal, and the sheet resistance probe, which can add substantial non-uniformity to sheet resistance measurements of implants into GaAs.

In order to determine the sensitivity of the technique to dose changes in the low 1E12 region at 100 keV, 6 different Si+ doses from 0.75E12 to 5E12 were implanted in optical densitometry substrates. Three substrates were implanted at each dose. Results of these implants are shown in Figure 2. This polymer system has high sensitivity for very low doses, where sensitivity is defined as:

\[ S = \frac{\text{Percent change in measured parameter}}{\text{Percent change in implant dose}} \]

A sensitivity of 1.0 would mean that doubling the implant dose would double the measured optical density. From the data in Figure 2, the sensitivity of optical densitometry is found to be 0.51 - 0.62 over the range 0.75E12 to 5E12. The figure also shows the excellent repeatability in mean optical density counts for the three wafers implanted at each dose. This sensitivity is high for the low 1E12 dose region, which is the dose region chosen for the channel implant in many microwave and digital GaAs IC applications.

THERMAL WAVE PROBE\(^1\)

The thermal wave technique measures damage done to the substrate by the implanted ions. A difficulty observed in earlier studies on Si+ into GaAs is that unimplanted GaAs substrates display a noise level which is two orders of magnitude higher than unimplanted Si substrates\(^2\). Consequently, to obtain an adequate signal to noise level for low dose implants, Si substrates must be used.

Figure 3 shows a map of the across-wafer uniformity in thermal wave units at 100 keV, 3E12, 28Si+ implant using this technique. As with optical densitometry, the standard deviation is indicative of the uniformity of the implant itself. In order to determine the sensitivity of the technique to dose changes in the low 1E12 region, 28Si+ implants were done at 100 keV with a doses of 2E12, 3E12, and 4E12 in to Si(100) substrates. Results of these implants are shown in Figure 4. The thermal wave technique has very low sensitivity (0.1 - 0.15) in this region. This is about one-fourth the sensitivity of optical densitometry in the same dose and energy range for Si+.

The thermal wave sensitivity was also explored in the high 1E13 dose range. 28Si+ implants were done at 150 keV and doses of 6.75E13, 7.5E13, and 8.25E13. Results of these implants are shown in Figure 5. The thermal wave technique has moderate sensitivity (0.4) in this high dose region.

COMPARISON OF EDDY CURRENT AND FOUR-POINT SHEET RESISTANCE PROBES\(^1\)

A commercially available eddy current probe was compared to a commercially available GaAs four point probe for accuracy and precision. Note that the GaAs four point probe differs from the standard four point probe used for measurements of sheet resistance on doped Si wafers in that special AC electronics and a different probe head are required for GaAs measurements. The precision study was done by studying the "discriminating power" of the two instruments. The discriminating power of an instrument is its ability to differentiate between different pieces of product (in this case 24 measurement locations on the same wafer) by making multiple measurements on each piece and studying the range of measurement error. Discriminating power is defined in detail in the AT&T Statistical Quality Control Handbook.

In this study, a single GaAs substrate (ID# 233x-45), was implanted with 28Si+ at 150 keV to a dose of 7.5E13. After anneal, the wafer was then measured by both probes at the identical 24 locations every day for five consecutive days. A table of X-Bar (average sheet resistance for 5 measurements) vs. measurement location number (1-24) was generated for each probe. From this table, plots were derived which look similar to standard SPC charts. These plots are shown in Figure 6 (for the eddy current probe) and Figure 7 (for the GaAs four point probe).

Each point on the X-Bar chart represents a different location on the wafer, or a different piece of product, if one assumes that the wafer is to be made into 24 devices. The control limits are derived from standard SPC formulas. If the X-Bar points stay in control, the measuring instrument can not see any difference between the measurement locations (pieces of the wafer). A good measurement instrument should have such narrow control limits that all or most of the X-Bar points are out of control.

In Figure 6, most of the X-Bar points fall outside the control limits, which are very narrow. Consequently, the eddy current probe is capable of reproducing its results very closely and can easily distinguish between the measurement locations on wafer 233x-45. It is very suitable for precise measurement of sheet...
resistance across a wafer, i.e. it has excellent discriminating power.

In Figure 7, most of the X-Bar points fall inside the control limits. This means that the lack of precision of the four point measurement is large enough to make the variations between measurement locations indistinguishable. The GaAs four point probe does not have the discriminating power to adequately characterize the across-wafer uniformity of wafer 233x-45.

As far as probe accuracy, the eddy current probe can be calibrated with NIST traceable standards over a wide range of sheet resistance. These standards are used by many fabs and are durable because they are n or p type Si substrates. Unfortunately, no equivalent standards exist for the GaAs four point probe. The NIST Si wafers will not work on the GaAs version of the four point probe because the probe tips are flat (to facilitate measurement of thin GaAs conducting layers) and do not penetrate the Si wafers enough to make a good contact.

APPLICATION OF THE EDDY CURRENT PROBE TO MMIC YIELD ENHANCEMENT

Clearly, the eddy current probe is the more precise and accurate sheet resistance probe. It is more suitable for yield enhancement applications where a variation in implantation dose, substrate donor or acceptor level, anneal furnace temperature, or other process variation must be detected to improve yield. In fact, the eddy current probe was used to measure blanket (unpatterned) channel implants into substrates from various suppliers. The probe determined that substrates manufactured by Supplier A produced a factor of two better across-wafer uniformity in sheet resistance than substrates manufactured by Supplier B.

A total of 191 MMIC wafers were then fabricated on wafers from both suppliers. Each MMIC wafer had nine van der Pauw structures located across it for the determination of the channel layer sheet resistance and its uniformity. The sheet resistance for this channel layer is approximately 600 ohms/square. The standard deviation of the channel layer sheet resistance (for 9 van der Pauw structures) as a function of supplier is shown in Figure 8. The median standard deviation was 14 and 31 ohms/square for Supplier A and B substrates, respectively. MMIC yield on Supplier A substrates was higher, in agreement with the eddy current probe and van der Pauw structure measurements.

REFERENCES

1. For the identity of the manufacturers of each probe, contact the author.

2. Dennis Kamenitsa, Eaton Corp., private communication.
3. For the identity of Suppliers A and B, contact the author.
Figure 3. Wafer map of thermal wave counts for a $^{28}$Si$^+$, 100 keV, 3E13 implant into a Si substrate. The mean count level is 705 and the standard deviation is 0.2%. The contour interval is 1.0%.

Figure 4. Thermal wave counts vs. dose for $^{28}$Si$^+$, 100 keV implants. 3 wafers were measured at each of the 3 dose levels.

Figure 5. Thermal wave counts vs. dose for $^{28}$Si$^+$, 150 keV implants. 3 wafers were measured at each of the 3 dose levels.

Figure 6. Plot of X-Bar of Resistance vs. Measurement Location Number for wafer 233x-45 as measured by the eddy current sheet resistance probe.

Figure 7. Plot of X-Bar of Resistance vs. Measurement Location for wafer 233x-45 as measured by the GaAs four-point sheet resistance probe.

Figure 8. Across wafer sigma of channel layer sheet resistance vs. substrate supplier for van der Pauw structures on MMIC wafers. Each data point represents sigma for one wafer.