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ION IMPLANTATION OF WIDE BANDGAP SEMICONDUCTORS.(U)

MAY 78 C L ANDERSON, H L DUNLAP, C L RAMILLER N00173-78-C-0070

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ION IMPLANTATION OF WIDE
BANDGAP SEMICONDUCTORS.

LEVEL II

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SECTION 1

INTRODUCTION AND SUMMARY

The primary goals of this program are to improve our understanding of the basic processes that control the electrical and physical properties of ion-implanted layers in GaAs and to exploit this understanding to develop a transferable technology base for reliable ion-implantation doping of GaAs. During the present one-year contract, the primary effort is to study, through duplicate processing and evaluation projects at Hughes Research Laboratories (HRL) and the Naval Research Laboratory (NRL), the factors that affect the transferability and reproducibility of implanting Si into GaAs, using "silicon nitride" as an annealing encapsulant.

The primary encapsulant deposition process being used for this program is plasma-enhanced deposition (PED) to react silane with nitrogen in the presence of argon. Both laboratories are using essentially identical commercial plasma reactors (LFE Corporation Model PND-301). The films deposited in these reactors are not pure Si_3N_4 but generally are silicon oxynitrides containing several atomic percent oxygen plus other contaminants such as hydrogen and traces of argon. Hence, the term "silicon nitride," which denotes Si_3N_4 , is not appropriate. The term "plasma nitride" will be used to denote the films actually prepared by PED.

Early in this report period, a substantial effort was made to establish gas flow conditions that would yield plasma nitride films with good encapsulation properties. Section 2 briefly describes the methods used and the results obtained. These preliminary studies yielded promising results, but reproducibility of the encapsulant properties was lacking. The reproducibility problem has not yet been eliminated.

When both laboratories had developed their plasma nitride technology to the point that a duplicate processing experiment was warranted, a standard Si implant was performed into several samples at each laboratory. These samples were then independently encapsulated and annealed. Electrical evaluation of all the samples was performed at each laboratory.

The results of this test of implant transferability are discussed in Section 3.

Recent Hall-effect measurements of the depth distribution of the electrical activity of Be/ion implants into GaAs performed by Code 5212, NRL, have indicated that channeling effects may cause significant departures of supposedly "random equivalent" implants from the LSS range distribution. A set of well-channeled $\langle 110 \rangle$ implants into well-characterized $\langle 100 \rangle$ GaAs was requested by Code 5212, NRL, for use as reference samples. The techniques used to prepare these samples are briefly described in Section 4.

The primary electrical evaluation technique used on this contract has been room-temperature Hall-effect analysis. This technique generally has been adequate to determine the success with which electrical activation of impurities has been achieved. As the plasma nitride encapsulants used improve, additional techniques will be required to assess electrical and atomic profiles, the degree of damage reduction achieved during annealing, and the generation-recombination mechanisms active within the implanted region. Section 5 describes improvements in analytic capability being instituted at HRL and suggests additional diagnostic tasks that will be useful for improving our understanding of ion implantation in GaAs in the near future.

During the period covered by this report, Mr. C.L. Ramiller left the Hughes Aircraft Company to assume a position with Intel Magnetics, Santa Clara, California. Mr. Ramiller had been responsible for the development of pyrolytic encapsulants for the annealing of implanted GaAs. A replacement for Mr. Ramiller is being sought.

SECTION 2

ENCAPSULANT DEVELOPMENT

During this reporting period, considerable effort was expended in the development of useful pyrolytic and PED "nitride" films for the encapsulation of ion-implanted GaAs. The principal thrust of our work on pyrolytic nitrides was to develop films with superior mechanical properties to the 600°C films described in our previous report.¹ Our earlier films were excellent barriers to Ga diffusion, but they caused the GaAs surface to crack. They were, therefore, useless for annealing implanted layers. The cracking problem is believed to result from a combination of three factors: (1) inherent stress in the nitride films; (2) thermal expansion mismatch between GaAs and Si_3N_4 ; and (3) the lack of plasticity in dense, stoichiometric Si_3N_4 films. The tensile stress in the films is reduced by lowering the growth rate. Thus, our previous experiments were done at slow growth rates ($\sim 200 \text{ \AA/min}$). Unfortunately, these films are extremely rigid and produce cracking in GaAs during 800°C anneals.

Investigators at MIT's Lincoln Laboratories have had considerable success using pyrolytic Si_3N_4 grown at $\sim 700^\circ\text{C}$ at very high growth rates ($\sim 4500 \text{ \AA/min}$).² Our hypothesis is that films deposited at such high growth rates are less vitreous than our earlier films and therefore deform plastically during annealing. Accordingly, we duplicated Lincoln Laboratories growth cycle, growing films of Si_3N_4 roughly 700 $\text{\AA}$ thick in 10 sec. Before beginning the silicon implantation transfer test described in Section 3, we had begun to see some promising results from this approach. Electrical results from two semi-insulating substrates implanted with $5 \times 10^{16} \text{ cm}^{-2}$ 100 keV Si^+ and annealed at 800°C for 30 min in purified argon are summarized in Table 1.

During this period, extensive evaluation of plasma nitride films has been performed. These studies were carried out using a modified LFE Corporation Model PND-301 plasma reactor. This type of unit is used at both HRL and NRL. The unit as received was far from leak-tight. Our first step was to render the system as leak-tight as possible. Complete

Table 1. Electrical Properties of Two Dice
Annealed under 700°C Pyrolytic Si₃N₄

Sample	Sheet Resistivity, $\Omega/\square$	Hall Electron Mobility, cm^2/Vsec	Sheet Electron Concentration, cm^{-2}
9701	126	2720	1.82×10^{13}
9703	144	2640	1.64×10^{13}

leak tightness under helium leak testing has never been achieved in our system. Although no "fast leaks" (<30 sec response time) can be detected, a major slow leak (>5 min response time) is always present because of the permeability of the silicone rubber bell jar seals on the system. This leak may not be significant for gases heavier than helium.

The PED systems at HRL and NRL were both modified along similar lines. The needle valve flow controllers for silane and nitrogen were replaced with Tylan Corporation mass flow controllers. An MKS Instruments Model 222 "Baratron" capacitance manometer was installed in the foreline of the unit at HRL to monitor the system pressure.

The principal technique used for analyzing plasma nitride encapsulation properties has been SEM imaging of the encapsulant and sample surfaces. Samples implanted with 10^{14} cm^{-2} and 10^{15} cm^{-2} 250 keV Se⁺ were encapsulated with plasma nitride films at a variety of silane flow rates. No significant difference in results was observed between films deposited on samples that received one fluence and those that received the other. The samples were then annealed at 800°C for 30 min in argon or forming gas. SEM examination was then performed. The sample was first examined with the encapsulant in place. These investigations showed that films grown at silane flow rates above those consistent with best mechanical adherence tended to "blister." That is, the encapsulant failed mechanically, leaving numerous roughly circular holes. Films grown at very high flow rates tended to buckle. Layers grown at silane flow rates below the optimum tended to crack or craze. With a narrow range of silane flow rates, the films exhibited few gross defects.

The encapsulant films were then removed in concentrated HF. SEM evaluation of the sample surfaces showed that samples annealed with "silicon-rich" encapsulants were generally badly pitted. Samples annealed under "silicon-deficient" films showed ridges (presumably of Ga_2O_3) corresponding to the cracks in the encapsulant. Samples annealed with the "optimum" encapsulant films generally showed only a few insoluble particles (again probably Ga_2O_3) and some surface texturing visible at 1000 X magnification.

All other measurable conditions were held constant in most of our tests. The measurable variables and their respective values are: nitrogen flow rate of 4.00 SCCM, rf power of 100 W, spacing between sample carrier/hot plate and quartz-silane dispersal jet of 0.75 in. (1.9 cm), spacing between rf coils and sample carrier/hot plate of 3.5 in. (8.9 cm), and sample temperature of 350°C. The foreline pressure with only nitrogen flowing was typically 90 μm Hg (12 Pa). Before silane was introduced, the system was operated for 5 min with only nitrogen flowing and an rf power of 100 W. After this 5-min "pre-burn," the plasma was extinguished. The silane flow was then started and stabilized. One minute after the "pre-burn," the plasma was again ignited. The "deposition time" (time with silane in the system with plasma ignited) was either 10 or 30 min.

Our initial experiments were performed using 5% silane in UHP argon. Using this silane source, the best films were obtained at dilute silane flow rates of roughly 18 SCCM (silane flow rate 0.9 SCCM). However, since severe problems with mass flow controller clogging were encountered with this mixture, we soon elected to use 1.5% silane in UHP argon.

Several dozen samples were prepared with the more dilute silane mixture at dilute silane flow rates in the range from 25 to 90 SCCM. With the HRL PED system and the silane source at HRL, plasma nitride films with optimum mechanical properties (principally determined from films roughly 2500 Å thick using deposition times of 30 min) are obtained for dilute silane flow rates of 34 to 36 SCCM (silane flow rate 0.51 to 0.54 SCCM). The silane flow rate with this gas mixture is nominally about one-half that obtained with the 5% silane mixture. In addition,

it is roughly one-half that used for optimum film properties by Code 5212, NRL. NRL found that their best films are obtained at dilute silane flow rates of 70 to 80 SCCM (1.05 to 1.20 SCCM silane flow) using nominally 1.5% silane in UHP argon and roughly equivalent system conditions. We probably obtained a bottle of dilute silane that is more concentrated than the nominal 1.5% requested.

Both Auger analysis and Rutherford backscattering have been used to analyze the composition of the plasma nitride films. In all cases, the material prepared is actually a silicon oxynitride typically containing 3 to 15 at.% oxygen. The composition of the material varies from run to run.

To determine if there was a systematic variation in film properties with successive runs, several simple experiments were performed. In one test, several 30-min runs were performed at 1.5% silane mixture flow rates of 35 SCCM. These runs were alternated with runs at 30 SCCM and 40 SCCM dilute silane flow. Auger analysis of the 35 SCCM showed no correlation of oxygen content in the films with the silane flow rate used in the previous run. There was very little consistency of oxygen concentration in the 35 SCCM films.

In a second test, four identical 30-min depositions were performed in succession during a single day following cleaning of the bell jar with CF_4/O_2 cleaning gas and subsequent operation of the system in the nitride deposition mode for 30 min with no sample present. The next day the entire procedure was repeated. The samples from both days were annealed simultaneously at 800°C for 30 min. SEM observation of the encapsulant surface showed that some samples exhibited cracking in roughly rectangular patterns and others exhibited cracks following areas of relatively constant radius. No correlation of the crack patterns with the position of the sample in the deposition sequence could be discerned.

Recent experiments with silicon oxynitrides deposited in the PED system using silane and nitrous oxide (N_2O) as reactants have indicated that the etch rate of the material in dilute HF varies over the surface of a large sample. This variation in etch rate is presumed to result

from nonuniform composition of the dielectric film. The cause of this nonuniformity is not known. One possibility is that the silane dispersal jet in the reactor fails to distribute the silane uniformly. Another possibility is that the three radial arms that transmit the dilute silane to the toroidal dispersal jet alter the plasma conditions near the sample surface under the arms, therefore causing changes in the film composition. Color patterns that resemble the placement of the radial arms can be seen easily in films deposited on large Si wafers. Experiments with a modified dispersal jet geometry intended to eliminate the shadowing effect will begin shortly.

By the time that the Si transfer test described in the next section was begun, some promising results had been achieved using the plasma nitride encapsulant. Implanted layers prepared using processing identical to that used to prepare the samples reported in Table 1, with the exception of the encapsulants, were coated with roughly 800 Å of plasma nitride during a 10-min deposition. For these dice, a dilute silane flow rate of 35 SCCM was used, and then they were coated on both sides with silicon oxynitride (composition approximately SiON) prepared using 4.00 SCCM N₂O in place of 4.00 SCCM N₂ (all other conditions were identical). Electrical evaluation of these samples yielded the results in Table 2.

Table 2. Electrical Properties of Four Dice
Annealed under Plasma Nitride

Sample Number	Sheet Resistivity, $\Omega/\square$	Hall Electron Mobility, cm^2/Vsec	Sheet Electron Concentration, cm^{-2}
Test Samples			
9714	205	1953	1.56×10^{13}
9715	387	1187	1.36×10^{13}
Control Samples			
488	3.6×10^7	5	3.3×10^{10}
489	2.5×10^7	8	3.2×10^{10}

SECTION 3

SILICON TRANSFER TEST Si 1

Four tests of the transferability and reproducibility of ion implantation processes using GaAs substrates have been performed by HRL and NRL. The first test, "Be 1," involved encapsulant-free annealing of Be-implanted GaAs at 550°C. It demonstrated both excellent transferability and an absence of ingot-to-ingot variations using four ingots of Cr-doped semi-insulating GaAs.³ Tests of the transferability of sulfur implantation and selenium implantation ("S 1" and "Se 1," respectively), each using encapsulant films from a single source, were performed during 1977.¹ The sulfur test used plasma nitride films prepared by the LEF Corporation. In the sulfur test, HRL and NRL achieved roughly equivalent results from samples implanted at room temperatures and annealed at 800°C, samples implanted at 250°C and annealed at 800°C, and samples implanted at room temperature and annealed at 900°C. The HRL results for samples implanted at 250°C and annealed at 900°C differed substantially from the NRL results. The selenium test, in which 600°C pyrolytic Si_3N_4 films prepared at HRL were used, was terminated when the samples implanted at HRL showed cracking and erratic electrical properties.

During this reporting period, the fourth transfer test, "Si 1," was performed. This test represents the first transfer test performed using encapsulant films prepared independently at each facility. Both HRL and NRL used plasma nitride as their principal encapsulant. Seven samples were prepared at NRL. Thirty samples, including 10 unimplanted control samples, were prepared at HRL. In addition, 12 samples, including 4 control samples, were prepared at HRL using each of three alternative encapsulants: pyrolytic SiO_2 prepared by the "silox" process (silane plus oxygen) at 400°C, pyrolytic Si_3N_4 prepared at 700°C, and pyrolytic SiO_2 prepared by the "Sperry-Rand" process (silane plus nitrous oxide) at 600°.

The substrate material was Cr-doped, semi-insulating GaAs from Crystal Specialties (ingot 2988). The samples were in the form of parallelepiped dice roughly 7 mm x 7 mm x 0.5 mm. All samples were

provided with implanted corner contacts using a $5 \times 10^{13} \text{ cm}^{-2}$ 100 keV silicon implant. All samples except the controls were given an overall implant of $10^{13}/\text{cm}^2$ 150 keV $^{29}\text{Si}^+$ using SiF_4 fuel. The implantations were performed at room temperature and "random" incidence. The mass-29 isotope of Si was used to prevent possible contamination of the ion beam with $^{28}\text{N}_2^+$. (A mass-29 nitrogen molecule $^{14,15}\text{N}$ exists but is only 0.8% of the total nitrogen concentration and, therefore, is not expected to contaminate the Si beam significantly.) All samples were annealed at 850°C for 30 min in flowing forming gas. This anneal cycle is considerably more severe than the 800°C anneal that gave good results in sulfur test S 1. It is, however, more in keeping with current GaAs device technology. Annealing in the 850 to 860°C range generally yields better electrical activity and doping profile than 800°C annealing if the encapsulant film is reliable.

Only the NRL samples have been measured at both facilities. The electrical results for these samples are presented in Table 3. One sample, number 462, yielded measurements inconsistent with the others and was not delivered to HRL. Electrical measurements performed on the remaining six samples at the two facilities are in good agreement. These results appear to indicate that very good electrical properties have been achieved at NRL: 81% electrical activity, good values of mobility, and standard deviations of mobility and sheet resistivity of only 8% of the mean value.

The HRL samples with plasma nitride encapsulation were prepared in two batches of 15. Nominally identical deposition parameters were used for each batch. The results for the first batch are presented in Table 4. Electrical results for 9 of the 10 test samples (eliminating one sample that apparently had not been implanted or had been implanted on the wrong side) differ significantly from those of the NRL samples. These samples exhibit 57% apparent electrical activity and higher sheet resistivity than the NRL samples. The mobility values of the HRL "first batch" samples are statistically indistinguishable from those of the NRL samples. The control samples from the first batch remained semi-insulating.

Table 3. Si Transfer Test Si 1
(NRL Samples, Plasma Nitride Cap,
NRL and HRL Measurements)

Sample Number	Sheet Resistivity, $\Omega/\square$		Hall Electron Mobility, cm^2/Vsec		Resistance Ratio
	NRL	HRL	NRL	HRL	
455	271	267	3060	3100	2.1
462	310	-	2310	-	-
466	250	265	3110	2970	1.4
468	229	237	3400	3300	3.2
715	243	245	3600	3620	1.0
743	219	221	3230	3220	3.0
747	229	223	2930	3070	1.7
Mean and Standard Deviation					
7 samples	250 $\pm$ 31		3090 $\pm$ 410		
6 samples	240 $\pm$ 19	243 $\pm$ 20	3220 $\pm$ 250	3210 $\pm$ 230	
81% electrical activity.					

The second batch of samples prepared at HRL using plasma nitride films gave quite different results. Of the 10 test samples, 2 exhibited resistance assymetries far from those expected because of geometric assymetries of the dice, and 1 exhibited excessive drift during the measurements. Electrical measurements on the remaining 7 samples, shown in Table 5, gave results comparable to those of the NRL samples: 79% apparent electrical activity and statistically equivalent values of sheet resistivity and mobility. In this case, however, the control samples failed to remain semi-insulating. Thus, it is likely that the high electrical activity and low sheet resistivity of the second batch of samples probably resulted from carriers not produced by activation of the implanted Si ions. Since no control samples were run at NRL, there

Table 4. Si Transfer Test Si 1
(HRL Samples (First Batch), Plasma
Nitride Cap, HRL Measurements)

Sample Number	Sheet Resistivity, $\Omega/\square$	Hall Electron Mobility, cm^2/Vsec	Resistance Ratio
Test Samples ^a			
552	326	2960	1.6
553	347	3460	1.0
554	342	3350	2.0
555	282	3760	1.2
556	428	2640	1.2
558	317	3480	1.1
559	311	3360	1.7
560	398	3020	1.3
561	301	3330	1.5
Mean and Standard Deviation	339 ± 47	3260 ± 330	
Control Samples			
603	1.3×10^6	460	2.6
604	1.3×10^5	480	2.6
605 ^b	4.6×10^9	240	1.3
606 ^c	1.1×10^7	8	1.1
607 ^b	3.8×10^9	360	3.5
^a 57% electrical activity.			
^b Current source saturated.			
^c Much drift.			

Table 5. Si Transfer Test Si 1
(HRL Samples (Second Batch), Plasma
Nitride Cap HRL Measurements)

Sample Number	Sheet Resistivity, $\Omega/\square$	Hall Electron Mobility, cm^2/Vsec	Resistance Ratio
Test Samples ^a			
564	224	3320	1.0
565	207	3630	1.0
567	249	3510	1.4
570	252	3190	1.0
571	230	3190	1.1
572 ^b	209	3490	4.4
573	273	3560	1.6
Mean and Standard Deviation	235 $\pm$ 24	3410 $\pm$ 180	
Control Samples			
611	346	3920	1.1
612	388	3650	1.1
613	483	4340	1.6
614	349	3770	3.3
Mean and Standard Deviation	392 $\pm$ 64	3920 $\pm$ 300	
^a 79% Electrical activity.			
^b Sample not square (broken).			

is no way to know whether the NRL results are partially influenced by substrate conversion during annealing.

Of the three batches of samples prepared at HRL using the alternative dielectric materials, only the samples provided with 600°C SiO₂ encapsulant films gave interpretable electrical results. Samples coated with both 400°C silox and 700°C Si₃N₄ gave erratic results. This is the first time in at least a year that the silox encapsulant has failed. Failure of the 700°C nitride was not surprising since we have had only limited experience with the 700°C deposition process.

The results from the samples given 600°C SiO₂ caps are presented in Table 6. Although the mobility values of these samples are quite good, the sheet resistance and apparent electrical activity of the samples are poor. Since our earlier work showed that 600°C SiO₂ is quite a good barrier to gallium outdiffusion, we doubt that surface decomposition is responsible for the poor electrical results achieved. A more likely explanation is that the mechanical properties of the encapsulant inhibit the complete annealing of inplant-induced lattice damage. Alternatively, this encapsulant may introduce a degree of damage into the crystal during annealing. The 600°C SiO₂ is denser and apparently more "vitreous" (less plastic) than 400°C silox SiO₂ and may suffer some of the mechanical problems encountered with our 600°C Si₃N₄ films.

Table 6. Si Transfer Test Si 1
(HRL Samples, 600°C SiO₂ Cap)

Sample Number	Sheet Resistivity, $\Omega/\square$	Hall Electron Mobility, cm^2/Vsec	Resistance Ratio
Test Samples ^a			
524	804	3550	1.7
525	815	3230	2.1
526	677	3790	1.4
527	1870	2700	1.3
528	1110	3470	2.0
529	896	3550	1.2
530	1130	2440	1.0
531	1190	3970	1.1
Mean and Standard Deviation	1060 $\pm$ 370	3340 $\pm$ 530	
Control Samples			
590 ^b	1.1 $\times 10^7$	4	622
591 ^b	1.3 $\times 10^7$	16	10
592 ^b	1.2 $\times 10^7$	- 3	12
593 ^b	3.6 $\times 10^6$	-28	10
^a 19% Electrical activity.			
^b Much drift.			

SECTION 4

CHANNELED Be IMPLANTS

Hall/stripping measurements performed by Code 5212, NRL, on Be-implanted GaAs samples have indicated that channeling effects may be responsible for some of the deviations of the electrical profile of the samples from that predicted for "random-equivalent" implants of Be into GaAs. Accordingly, Code 5212, NRL, requested that we prepare a set of GaAs samples from a well-characterized Cr-doped ingot implanted with the beam incident parallel to a $\langle 110 \rangle$ axis of the crystal. (The $\langle 110 \rangle$ axis is the optimum channeling axis for zincblende-type lattices.) The experiment would have been quite straightforward if well-characterized (110) wafers had been available. Unfortunately, our supply of reliable Cr-doped substrates consisted entirely of (100) wafers.

On a (100) GaAs wafer, the surface normal is nominally a [100] axis. There are four $\{110\}$ axes that project out from this surface at a 45° angle to the surface normal: $[110]$, $[101]$, $[\bar{1}10]$, and $[10\bar{1}]$. There are also four $\langle 110 \rangle$ axes that are at 90° to the surface normal: $[0\bar{1}1]$, $[0\bar{1}\bar{1}]$, $[01\bar{1}]$, and $[011]$. The last four axes are the surface normals to the $\{011\}$ cleavage planes that form the edge faces of a typical cleaved die used for implant studies in this contract. If such a die were perfectly square, the plane which contains both the [100] surface normal to the wafer and any one of the $\langle 110 \rangle$ axes that project at 45° to the surface normal would pass through two corners of the surface of the die.

To produce a channeled implant it is necessary to position the sample so that a single crystal axis is collinear with the impinging ion beam. Thus, to perform a $\langle 110 \rangle$ channeled implant into a (100) GaAs wafer, the wafer must be oriented at a 45° angle relative to the beam and must be rotated so that one of the four $\langle 110 \rangle$ channeling axes is collinear with the beam.

The ion channeling system at HRL is equipped with a sample goniometer that permits aligning sample axes to within 0.02° of the direction of the ion beam. Unfortunately, this goniometer can tilt the sample a maximum of 35° . Thus, to perform a $\langle 110 \rangle$ implant into a (100) wafer, an

additional tilt must be supplied by mounting the sample on a wedge. Accordingly, we prepared a wedge with a 45° apex angle to tilt the sample at 45° to the ion beam when no tilt was indicated on the goniometer controls.

To properly rotate the samples, the samples were provided with cleaved edges. A well-cleaved sample has quite straight edges. Scribed lines were provided on the mounting wedge to help in aligning the sample. These lines formed a 90° angle that was bisected by a line running directly up the slope of the wedge. By positioning two edges of the sample accurately along a pair of these guidelines, the sample was properly rotated so that alignment of the crystal could be performed using our standard alignment procedure.

The actual implant was performed after the sample had been aligned to within 0.02° of a $\langle 110 \rangle$ axis using proton backscattering. In our channeling system, the deflection plates that raster-scan the ion beam are located roughly 3 m from the sample. Using this deflection system, a 1 cm x 1 cm area normal to the beam can be scanned while maintaining beam alignment within $\pm 0.12^\circ$ of a channeling axis. With the sample mounted on the 45° wedge, the actual implanted area is 1 cm x 1.4 cm and the ion fluence measured in cm^{-2} must be reduced by a factor of 1.4 to account for the oblique incidence of the beam.

Using these techniques, 4 samples from Crystal Specialties ingot 2988 were implanted with 10^{13} cm^{-2} 150 keV Be^+ and were delivered to Code 5212, NRL, for evaluation. The penetration of this implant will be roughly equivalent to that of a 110 keV implant into a (110) wafer because of the foreshortening that results from the oblique incidence of the implant.

SECTION 5

DIAGNOSTIC IMPROVEMENTS

Hall-effect analysis is the primary technique being used for electrical evaluation of the implanted samples for this program. For this purpose, we use a computer-controlled Hall-effect system that controls all the variables of the Hall effect and sheet resistivity measurements except for the absolute value of the magnetic field. All lead switching and magnetic field reversals are performed under computer control. With this system, roughly 80 independent measurements are performed within 6 to 10 min to establish the sheet resistivity and Hall coefficient of a single sample. Very complete information concerning the electrical asymmetry of the sample and the drift of the measured values are provided on the computer output.

More complete diagnostics of the properties of the implanted layers are clearly needed in view of the significant improvements in electrical activation of implanted layers recently achieved at HRL and NRL using plasma nitrides. (Section 3 describes the latest results.) In particular, electrical profile measurements will be very important in determining if redistribution of the implanted species is occurring (or if the electrical and atomic profiles differ). Hall/stripping measurements are one method of doing this, but they are very time-consuming and require great care if an accurate depth scale is to be maintained. Capacitance-voltage (C-V) analysis is less time-consuming in the measurement stage but generally requires lightly doped epitaxial material on heavily doped substrates to be used if really critical profile analysis is to be performed.

HRL has a commercial analog C-V profiling system that is used for routine diagnostic work. Units of this type generally are not particularly suitable for critical work on rapidly varying profiles (such as Gaussian implants) because the test voltages applied to determine dC/dV may degrade the resolution. (Ref. 4 discusses the problem of determining dC/dV in an analog system.) A digital data acquisition system has been ordered for the purpose of determining impurity profiles by

computer-controlled C-V measurements. Using this system, low test levels (10 mV rms) will be applied at all times, and the computer will control the bias voltage steps applied to ensure that optimum depth resolution is maintained.

In addition, we are presently establishing the capability to perform deep level transient spectroscopy (DLTS) and low-temperature photoluminescence (PL). The combined use of DLTS and PL provides a very powerful capability for identifying impurity energy levels over a large fraction of the bandgap region. DLTS can provide quantitative information on impurity energy level, capture cross-section, and concentration. PL provides quantitative energy level information and useful concentration information. Attempts to quantify PL concentration measurements are being made at several establishments. PL intensities provide a very useful measure of the degree of lattice disorder in implanted regions by providing a direct indication of the relative radiative lifetime. The use of DLTS and PL on this program in the near future should provide very useful information concerning the defect levels introduced during ion implantation and annealing procedures. This information will then provide a basis for developing optimized techniques that will permit controlling the defect-generation processes.

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