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LASER ANNEALING OF GaAs

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Rockwell International/Science Center
Thousand Oaks, California 91360

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The results of pulsed laser annealing of ion implanted GaAs are compared with those obtained from pulse electron annealing of similar samples. Surface morphology studies indicate that the surfaces of electron beam annealed samples are generally more uniform than for laser annealing, however, above a certain threshold energy density, cracks in the GaAs are observed for electron beam annealed samples. Channeling analysis of electron beam annealed layers shows good recrystallization of amorphous GaAs and an indication that damage is introduced when the electron pulse energy density is too high. The

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activation of 300 keV Se ions implanted at room temperature to a dose of $1 \times 10^{15} cm^{-2}$ is compared for laser and E-beam annealing. Higher sheet electron concentrations were usually observed for the E-beam case.

Originator-supplied Keywords include: Pulsed annealing.

1 x 10 to the 15th power/sq cm

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FOREWORD

The research covered in this report was carried out in the Integrated Circuits Group of the Rockwell International Science Center. The principal contributors were J.L. Tandon and F.H. Eisen. Experimental assistance was provided by E. Babcock. The assistance of Anton Greenwald, Spire Corporation (electron beam irradiation); Curtis Robnett, Korad Lasers (laser irradiation); and Ilan Golecki, Caltech (backscattering measurements) is gratefully acknowledged.

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TECHNICAL SUMMARY

The goals of this program are to investigate the possibility of annealing implanted layers in GaAs using a laser or an electron beam, and to characterize the properties of these implanted and annealed layers. This section summarizes some of the results obtained during the second quarter of the program.

1. Irradiation from a pulsed electron beam (mean electron energy $\approx$ 20keV, $t_p \approx 10^{-7}$s) has been found to anneal the damage produced by ion implantation in semi-insulating GaAs. The energy densities needed to achieve annealing exhibit a narrow window which seems to be a function of the implantation dose.

2. Surface morphology studies of irradiated samples indicate that the surfaces of electron beam annealed samples are generally more uniform than the surfaces of ruby laser annealed samples. However, above a certain threshold energy density, cracks in the GaAs are observed for electron beam annealed samples.

3. Channeling measurements of electron beam annealed layers show good recrystallization of amorphous GaAs and an indication that damage is introduced when the electron pulse energy density is too high.

4. Electrical activity measurements made on 300 keV Se^+ implanted samples indicate higher activation of Se^+ ions in electron beam annealed samples than in ruby laser annealed samples implanted with the same dose. This result is generally found to be true for high dose ($> 10^{15}cm^{-2}$) implants.

5. Electron concentrations in excess of $10^{19}/cm^3$ were measured in the $10^{15}/cm^2$ Se^+ implanted and electron beam annealed samples. This number is of the same order as measured in the ruby laser annealed samples, and at least a factor of two higher than the highest electron concentration obtained in the thermally annealed samples.

6. Semi-insulating GaAs samples implanted with low dose of Se^+ ions ($< 10^{14}/cm^2$) and irradiated with either a ruby laser pulse or an electron beam pulse showed poor or no measurable activation of the Se^+ ions. The reason for this is not clear, and is being investigated.

1.0 INTRODUCTION

In this second quarterly report, a summary of results is provided on the pulsed-annealing of implanted semi-insulating GaAs when exposed to irradiation from both a single ruby laser pulse (λ = 0.694μm, 1.5x10^{-8}s), or a single electron beam pulse (mean electron energy ≈ 20 keV, t_p ≈ 10^{-7}s). The ability to use pulsed techniques to anneal post-implantation damage seems attractive in GaAs, especially if one could accomplish it without the use of encapsulants, which are typically required during conventional thermal annealing. The motivation to explore pulsed techniques for annealing stems from the speculation that during the short time durations involved during exposure, significant dissociation of GaAs may be prevented. In addition, pulsed annealing techniques should provide a means for localized annealing and also allow for flexibility in the depth of annealing by controlling the parameters of the beams.

Several experiments were performed under various conditions to study the effects of laser and electron beam pulses on GaAs. The results of the investigations are grouped in terms of the type of analytical studies performed. In Section 2, surface morphology studies on irradiated samples prepared under various conditior~ of both laser and electron beam exposure are described. Electron beam annealed samples are found to be generally more uniform laterally when compared to laser annealed samples. In Section 3, backscattering measurements with channeling performed on pulse irradiated samples are discussed. Measurements indicate good annealing of post-implantation damage after pulsed-beam exposures with proper energy densities. Electrical measurements made on the pulsed-annealed samples are described in Section 4. Good electrical activation for high dose (>10^{15}/cm^2) 300 keV Se implants in semi-insulating GaAs is observed after annealing by a laser or an electron beam pulse. Finally, Section 6 contains concluding remarks, together with future plans for experiments and investigations.

2.0 SURFACE MORPHOLOGY STUDIES

In this section, Nomarski optical photographs of the surfaces of GaAs samples after irradiation with the laser or the electron beam pulses are presented. The surfaces of several GaAs samples, implanted or unimplanted, coated and uncoated with Si_3N_4 were examined after pulsed-irradiation with different energy densities.

2.1 Laser Irradiation

2.1.1 Laser Exposure of Virgin Semi-Insulating GaAs

Wafers of semi-insulating GaAs were exposed in air to ruby laser pulses with various energy densities. Figure 1 shows photographs of the surfaces after irradiation. As can be seen, even at 0.72 J/cm^2 (energy density less than the threshold value for annealing implanted GaAs[1]), the exposed area indicates melting in localized regions, which is possibly due to hot spots in the laser. As the energy density is increased, evidence of melting over larger areas is observed (see Fig. 1a-d). Generally, with the ruby laser, resolidification after melting is almost always found to be non-uniform. The spatial energy distribution in the laser spot seems to be a factor in obtaining exposures that appear featureless as viewed under the optical microscope magnification.

2.1.2 Laser Exposure to Implanted Semi-Insulating GaAs

Figure 2 shows photographs of the surfaces of semi-insulating GaAs samples implanted with 10^{15} 300 keV Se^+ ions/cm^2 and irradiated with laser pulses of various energy densities. Increased melting over larger areas with increasing energy density is again observed. These photographs probably represent the regions with the worst texture when viewed under the microscope. However, the samples were also found to contain regions which were essentially featureless, as evidenced by Fig. 3, where photographs of these exposed to the lowest (0.75 J/cm^2) and the highest (1.51 J/cm^2) values of laser energy densities (see Fig. 2) are shown. It should be noted that all samples with surfaces shown as in Fig. 2 were found to possess good electrical activation of

GaAs

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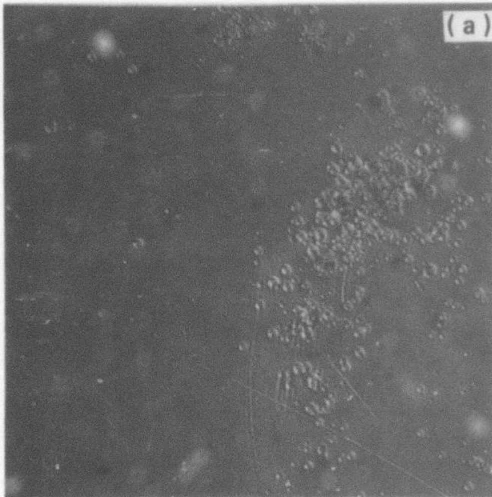
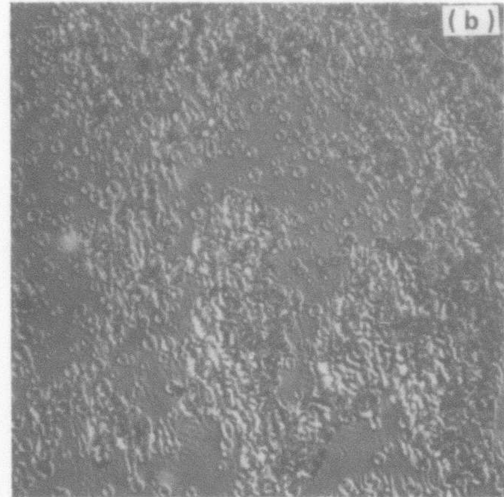
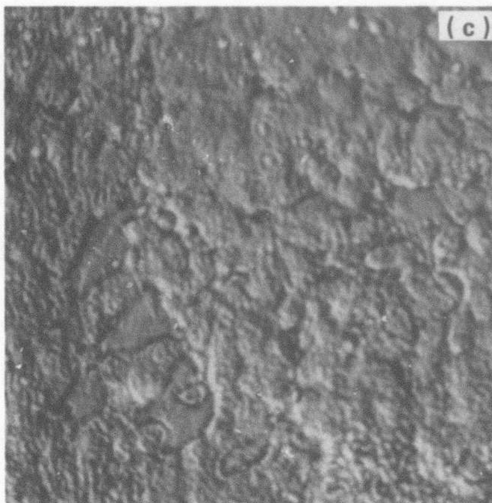


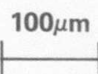
0.72 J/cm^2

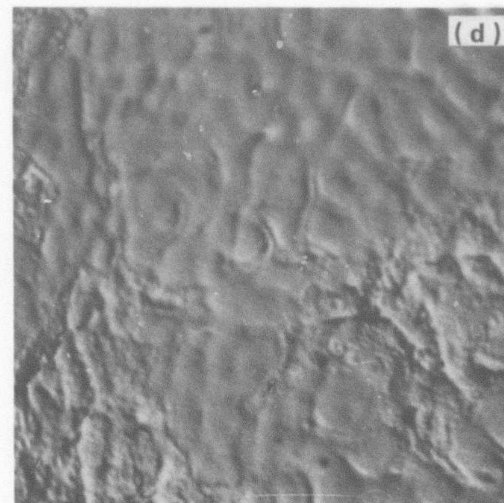


1.20 J/cm^2



1.75 J/cm^2



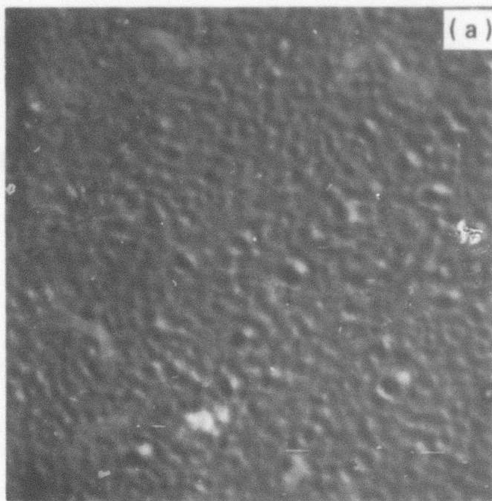


2.01 J/cm^2

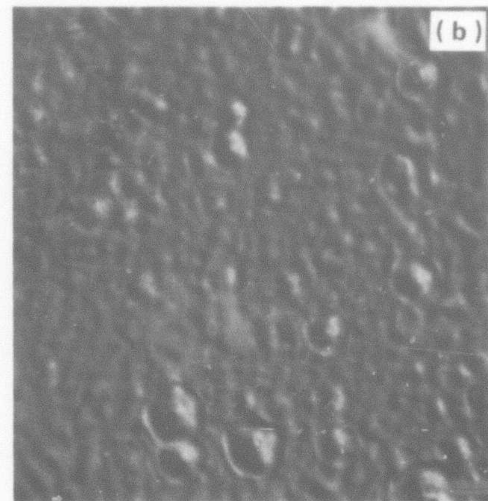
Fig. 1 Surface morphology of semi-insulating GaAs after irradiation with a ruby laser pulse of energy density: (a) 0.72 J/cm^2, (b) 1.20 J/cm^2, (c) 1.75 J/cm^2 and (d) 2.01 J/cm^2.

Se→GaAs, R. T., 300 keV, 1 x 10^{15} cm^{-2}
RUBY LASER ANNEAL, NO ENCAPSULANT

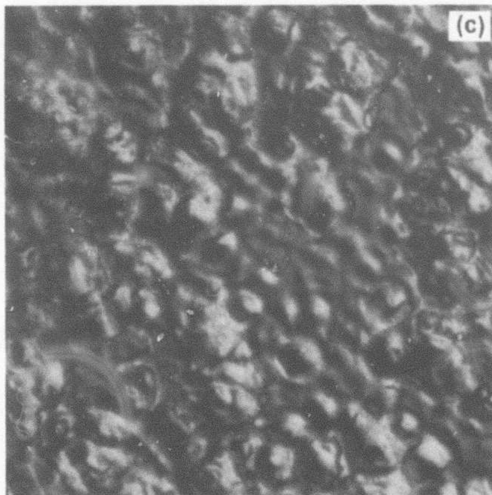
SC79-4280



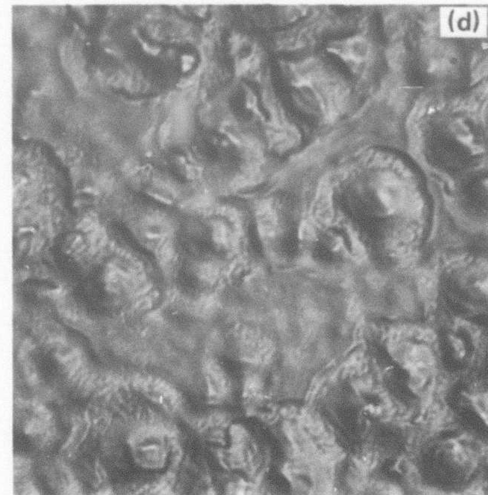
0.75 J/cm^2



0.94 J/cm^2



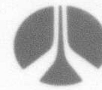
1.12 J/cm^2



1.51 J/cm^2

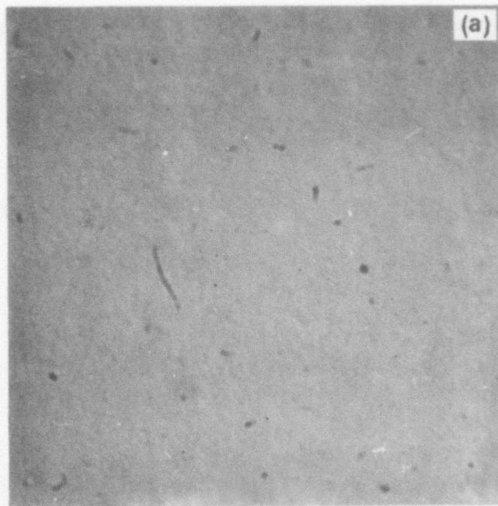
20μm

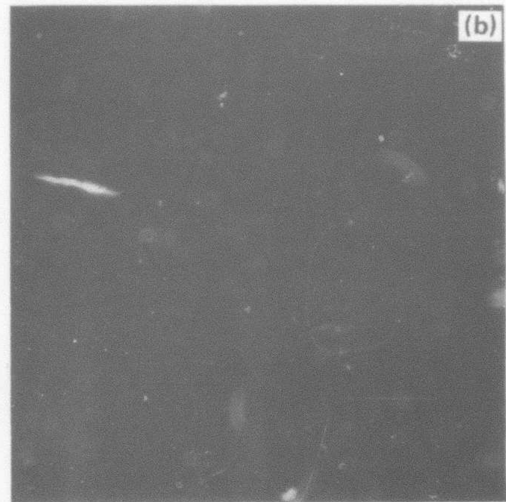
Fig. 2 Surface morphology of implanted (300 keV, 1x10^{15} Se^+/cm^2 semi-insulating GaAs after irradiation with a ruby laser pulse of energy density: (a) 0.75 J/cm^2, (b) 0.94 J/cm^2, (c) 1.12J/cm^2, and (d) 1.51 J/cm^2.



Se → GaAs, R. T., 300keV, 1×10^{15} cm^{-2} RUBY
LASER ANNEAL, NO ENCAPSULANT

SC79-4281





0.75 J/cm^2 20μm 1.51 J/cm^2

Fig. 3 Surface morphology of selected small uniform regions from the samples shown in Fig. 2(a) and (d).

the Se ions (see Section 4) over areas of dimensions 7mm x 7mm employed for measurements.

2.1.3 Laser Exposure of Implanted and Encapsulated Semi-Insulating GaAs

Semi-insulating GaAs samples were implanted with 300 keV 10^{15} Se^+ions/cm^2 and irradiated with ruby laser pulses after being capped with ~1000A of reactively sputtered Si_3N_4 films. Figure 4 depicts the surfaces of these samples after irradiation with different energy densities of the laser. It is found that the Si_3N_4 film begins to crack, presumably due to thermal stresses, when exposed to a laser pulse with energy density as low as 0.59 J/cm^2. Larger cracks are introduced in the Si_3N_4 film with a laser pulse of higher energy density (Fig. 4b), and with a pulse of energy density >1.3 J/cm^2, the Si_3N_4 film is completely vaporized from the area exposed to the laser beam (Figs. 4c and d). The samples in Figs. 4c and 4d also seem to indicate melting and resolidification of the GaAs surface beneath. The texture of the surfaces after resolidification, however, appears to be somewhat finer than the texture of the surfaces of uncoated samples exposed to laser irradiation (compare Fig. 4 with Figs. 1 and 2). Since the Si_3N_4 film cracks or vaporizes when the coated samples are irradiated with laser energy densities sufficient for successful annealing, the Si_3N_4 film does not seem to function in protecting the stoichiometry of the GaAs surface as in conventional thermal annealing of implanted GaAs. It should be noted, however, that the Si_3N_4 film may assist in homogenizing the spatial absorption of the laser energy in the underlying GaAs surface which may contribute in the more uniform resolidification of the melted GaAs layer (see Figs. 1, 2 and 4).

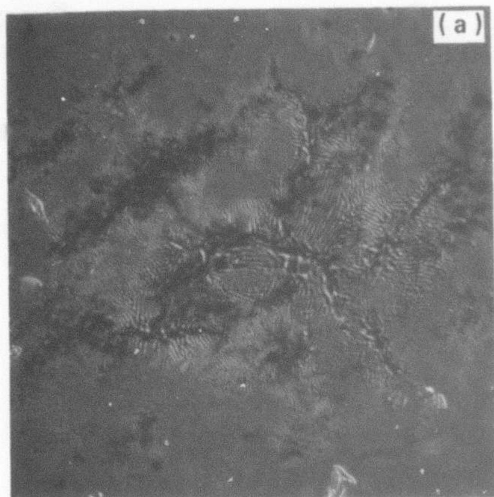
2.2 Electron Beam Irradiation

2.2.1 Electron Beam Exposure to Low-Dose Implanted Semi-Insulating GaAs

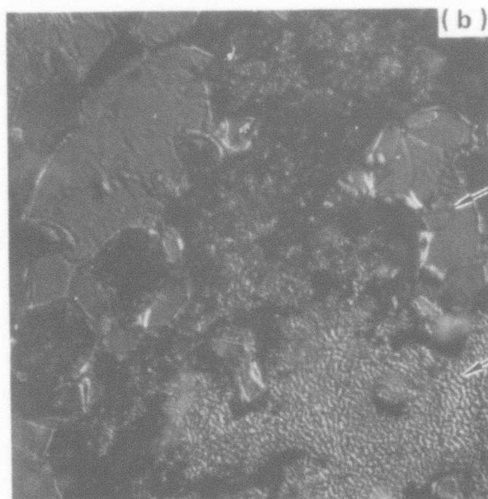
In Fig. 5, the surfaces of semi-insulating GaAs samples implanted with $3x10^{12}$ 300 keV Se^+ions/cm^2 and irradiated with various values of electron beam energy densities are compared with the surface of the as-implanted sample. The electron beam exposed area seems to be much better in uniformity compared to the laser exposed areas (compare Fig. 5 with Figs. 1 and 2). The

Se → GaAs, R. T., 300 keV, 1 x 10^{15} cm^{-2} RUBY
LASER ANNEAL, 1000Å Si_3N_4

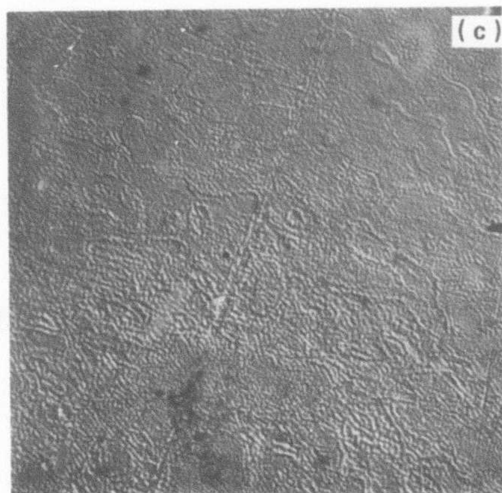
SC79-4282



0.59 J/cm^2

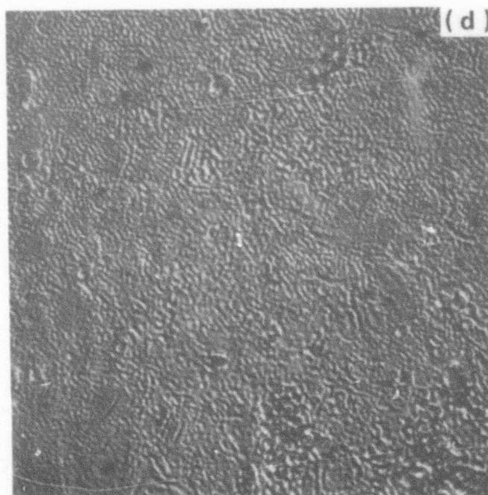


0.72 J/cm^2



1.3 J/cm^2

100μm

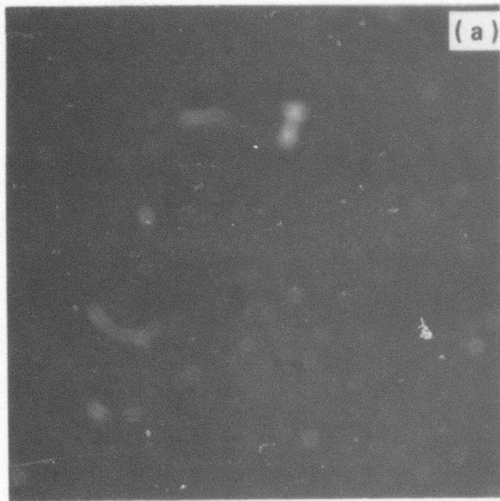


1.75 J/cm^2

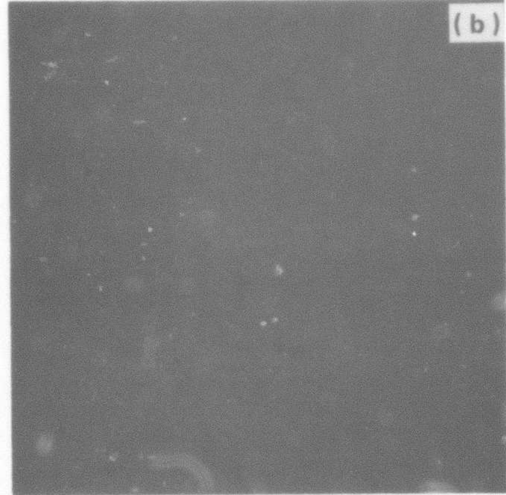
Fig. 4 Surface morphology of semi-insulating GaAs samples coated with ~1000Å Si_3N_4 film after irradiation with a ruby laser pulse of energy density: (a) 0.59 J/cm^2, (b) 0.72 J/cm^2, (c) 1.3J/cm^2, and (d) 1.75 J/cm^2. All samples were implanted with 300 keV, $1x10^{15}cm^{-2}$ Si^+ions at room temperature prior to Si_3N_4 coating and laser irradiation.

Se→GaAs, R. T., 300 keV, 3 x 10^{12} cm^{-2} ELECTRON BEAM ANNEAL, NO ENCAPSULANT

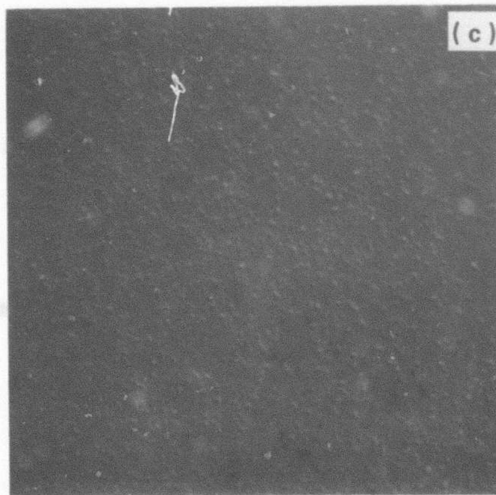
SC79-4283



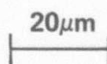
NO ANNEAL

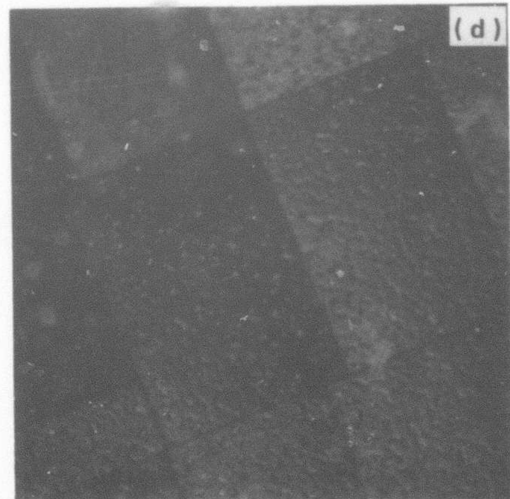


0.42 J/cm^2



0.67 J/cm^2





1.05 J/cm^2

Fig. 5 Surface morphology of implanted (300 keV, 3×10^{12} Se^+/cm^2) semi-insulating GaAs samples after (a) implantation and after irradiation with an electron beam pulse of energy density, (b) 0.42 J/cm^2, (c) 0.67 J/cm^2, and (d) 1.05 J/cm^2.

areas shown in Fig. 5 should be considered as representative of typical surface morphology over the electron beam irradiated spot. At an electron beam energy density of 0.67 J/cm^2 (Fig. 5c), considerable pitting of the surface is observed which is followed by cracking of the surface at a higher energy density of 1.05 J/cm^2 (Fig. 5d). The cracks are probably caused by thermal stresses and seem to occur along well defined planes. Similar cracks have also been observed in Si samples irradiated with electron beam pulses of high energy densities.[2]

2.2.2 Electron Beam Exposure of High Dose Implanted Amorphous Layers in Semi-Insulating GaAs

Semi-insulating GaAs wafers were implanted with $1x10^{15}$ 300 keV Kr^{+}ions/cm^2 at room temperature to generate an amorphous layer ~2000Å thick (Section 3, Fig. 7). Figure 6 shows the surface morphology of these samples after irradiation with different energy densities of electron beam pulses. For comparison, the surface of the as-implanted sample is also shown (Fig. 6a). It is interesting to note that the energy density threshold for the surface damage by the electron beam pulse in this set of samples is different from the samples implanted with low-dose ($3x10^{12}/cm^2$) of Se ions (see Fig. 5). The sample irradiated with an electron beam pulse of 0.67 J/cm^2 (Fig. 6c) shows a surface which is indistinguishable from the surface of the as-implanted samples (Fig. 6a), except for the color change due to the recrystallization of the amorphous layer (see Section 3). Pits such as seen on the surfaces of low dose implanted samples after electron beam irradiation (Figs. 5c an d) are almost absent on the surfaces of high dose implanted samples irradiated with similar energy densities of electron beam pulses (Figs. 6c and d). The type of surface structure (Fig. 6d) indicates that some kind of damage is introduced by the electron beam pulse of 1.05 J/cm^2 in the high dose implanted samples, but it is not cracking of the surface. This kind of structure is not found on the surfaces of low dose implanted and electron beam irradiated samples (see Fig. 5). From this surface morphology study of electron beam irradiated samples, it is quite clear that in order to achieve effective annealing of ion implanted semi-insulating GaAs without introducing

Kr → GaAs, R. T., 300 keV, 1 x 10^{15} cm^{-2} ELECTRON
BEAM ANNEAL, NO ENCAPSULANT

SC79-4284

(a) NO ANNEAL

(b) 0.42 J/cm^2

(c) 0.67 J/cm^2

(d) 1.05 J/cm^2

20μm

Fig. 6 Surface morphology of implanted (300 keV, 1x10^{15} Kr^+/cm^2) semi-insulating GaAs samples after, (a) implantation and after irradiation with an electron beam pulse of energy density, (b) 0.42 J/cm^2, (c) 0.67 J/cm^2, and (d) 1.05 J/cm^2.

additional damage, the energy density of the electron beam pulse should be adjusted according to the ion implantation dose.

3.0 BACKSCATTERING MEASUREMENTS WITH CHANNELING

Channeled backscattering spectra with $^4He^+$ ions were obtained to determine the recrystallization of amorphous implanted layers in semi-insulating GaAs after irradiation by laser or electron beam pulses. In this section, some of these measurements are described.

3.1 Laser Annealing

The recrystallization of implanted amorphous layers by ruby laser pulses has been demonstrated earlier[1] and will not be repeated here. In general, a ruby laser pulse of 1.2 J/cm^2 or higher is found to anneal completely an amorphous layer about 2200A thick produced by implantation in GaAs.

3.2 Electron Beam Annealing

Figure 7 shows backscattering spectra obtained with a 2.4 MeV He^+ beam aligned in the <100> direction of several semi-insulating GaAs samples. A 300 keV Kr^+ implantation to a dose of 10^{15}/cm^2 is found to produce an amorphous layer about 2200A thick in GaAs as measured by comparing the backscattering yields from the random and the <100> aligned spectra obtained from the as-implanted sample. After an electron beam pulse irradiation of 0.67 J/cm^2, the amorphous layer disappears and the aligned backscattering yield from this sample compares well with that obtained from an unimplanted sample, indicating good recrystallization. It is interesting to note that an increase in the energy density of the electron beam pulse to 1.05 J/cm^2 results in additional damage, as indicated by the increased aligned backscattering yield. This additional damage introduced by the electron beam pulse was also visible on the surface of the sample (see Fig. 6d).

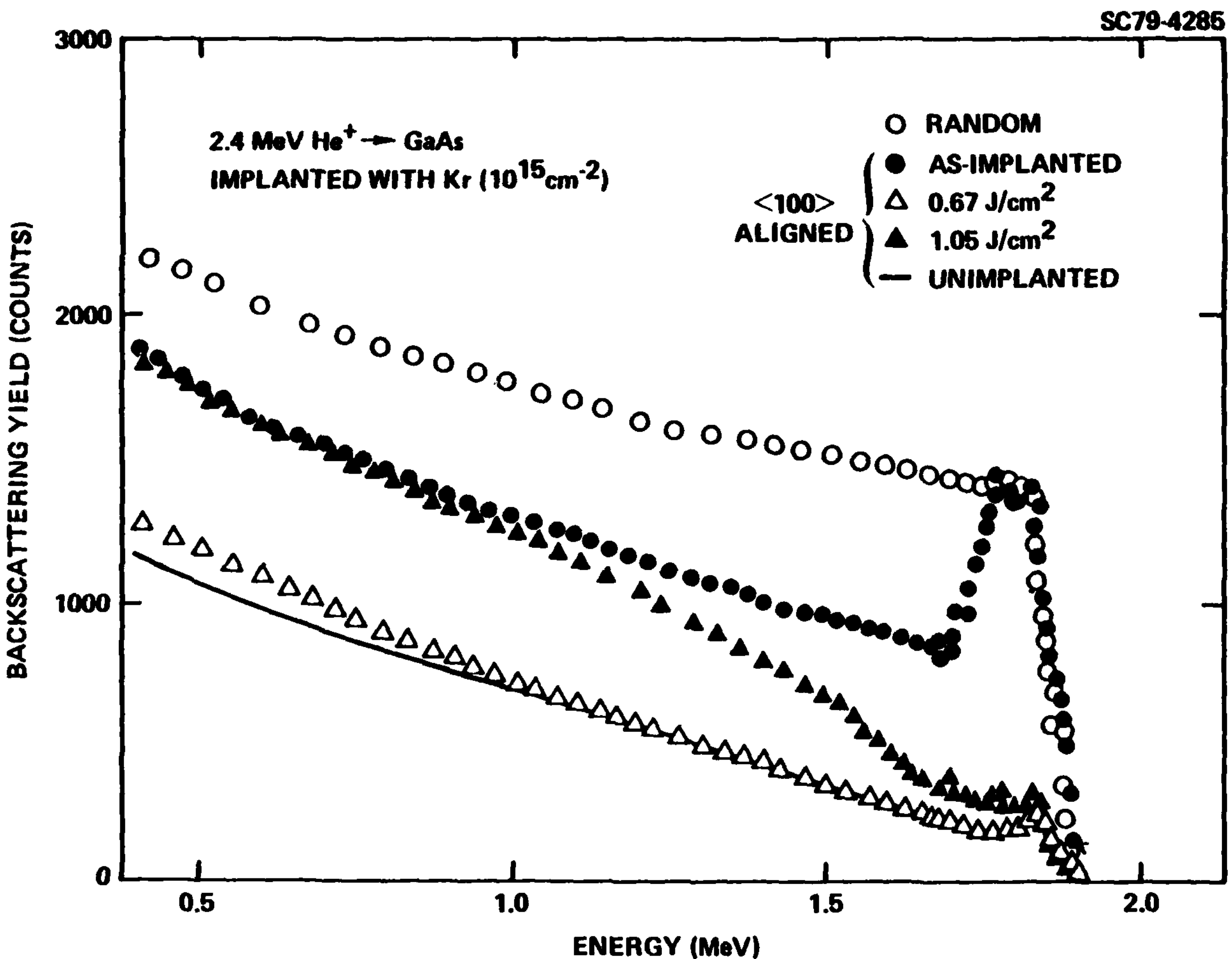


Fig. 7 Random and channeled 2.4 MeV He^+ backscattering spectra obtained from several implanted (300 keV, $1x10^{15}$ Kr^+/cm^2) and electron beam irradiated GaAs samples: random (o), <100> aligned after implantation (•), <100> aligned after implantation and irradiation with an electron beam pulse with energy density 0.67 J/cm^2 (Δ) and 1.05 J/cm^2, (Δ). For comparison, the <100> aligned spectrum from an unimplanted sample (-) is also shown.

4.0 ELECTRICAL MEASUREMENTS

Resistivity and Hall effect measurements were made on Se implanted semi-insulating GaAs samples after irradiation by either laser or electron beam pulses. For the measurements, an area of about 7mm x 7mm within the irradiated region was used to etch a Van der Pauw type mesa provided with Au-Ge/Pt alloyed ohmic contacts. In some cases, differential Hall effect measurements of the stripping type were also performed to determine the depth distribution of electron concentrations.

In Fig. 8, sheet electron concentration (N_S), effective mobility (μ_e), and sheet resistance (ρ_s) measured in several samples are plotted against the incident energy density of pulsed irradiation from either the laser or the electron beam. All samples were implanted with 10^{15} 300 keV Se^+ions/cm^2 at room temperature prior to annealing. All anneals were performed without an encapsulant. The values of N_S, μ_e, and ρ_s measured in samples ℓ and r capped with AlN and thermally annealed are also shown in Fig. 8 as dotted lines for comparison. The thermally annealed sample was implanted with a similar dose and energy of Se ions at 350°C, and the annealing was performed at 900°C for 10 min. in H_2 ambient. All the laser and the electron beam annealed samples show higher activation of Se ions (higher values of N_S) when compared to the thermally annealed sample. In addition to exhibiting more uniform surfaces (see Section 2), the electron beam annealed samples also show higher activation of Se ions compared to the laser annealed samples. The variataions in N_S, μ_e and ρ_s in the laser annealed samples, as a function of incident energy densities, may result from non-uniformities in the laser beam spot.

Figure 9 gives depth profiles of electron concentration (n) and mobility (μ) for two samples implanted with 10^{15} 300 keV Se^+ions/cm^2 and annealed with two different energy densities of electron beam pulse, one with 0.42 J/cm^2 and the other with 0.67 J/cm^2 (see Fig. 8). The electron concentration profiles exhibit similarities in the two cases, and they appear deeper than the LSS calculated profile.[3] The peak electron concentrations are found to reach levels higher than 10^{19}/cm^3, which are also measured in the

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Se → GaAs, 300 KeV, R. T.
$1 \times 10^{15} cm^{-2}$
○ RUBY LASER ANNEAL
● ELECTRON BEAM ANNEAL
--- THERMAL ANNEAL (900°C)

$N_S (cm^{-2})$
2×10^{14}
10^{14}
8×10^{13}
6×10^{13}
4×10^{13}
2×10^{13}
N_S

$\mu_e \left(\frac{cm^2}{VS}\right)$
2×10^{3}
10^{3}
8×10^{2}
6×10^{2}
4×10^{2}
2×10^{2}
μ_e

$\rho_S \frac{\Omega}{\square}$
2×10^{2}
10^{2}
8×10^{1}
6×10^{1}
4×10^{1}
ρ_S

0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
INCIDENT ENERGY DENSITY (J/cm^2)

Fig. 8 Sheet electron concentration (N_S), effective mobility (μ_e) and sheet resistance (ρ_S) measured in the pulse-annealed GaAs samples vs the incident energy density of laser or electron beam irradiation. All samples were implanted with 300 keV, 1×10^{15} Se^+/cm^2 at room temperature prior to pulse-annealing. As a comparison, values of N_S, μ_e and ρ_S measured for a thermally annealed sample are also shown by dotted lines. The thermally annealed sample was implanted with a similar dose and energy of Se ions and capped with a film of AlN prior to annealing in H_2 ambient at 900°C for 10 min.

Fig. 9 Electron concentration (n) and mobility (μ) vs depth (d) profiles of two electron beam annealed samples, one with a pulse of 0.42 J/cm^2 (o) and the other with a pulse of 0.67 J/cm^2 (●). Both samples were implanted with 300 keV, $1x10^{15}$ Se^+ ions/cm^2 at room temperature prior to electron beam exposure. The dotted line (μ_{Sze}) represents the estimated value of mobility[5] for the peak electron concentration measured in the n-profile.

laser annealed samples.[4]

Several samples implanted with lower doses ($3x10^{12}$ - $1x10^{14}/cm^2$) of 300 keV Se^+ ions were also irradiated with the laser or electron beam pulses of similar energy densities as employed for annealing the $10^{15}/cm^2$ implants. These samples showed poor or no activation of the implanted Se. As an example, a $10^{14}/cm^2$ implant exhibited an activation of only 6.1% after irradiation with an electron beam pulse of 0.67 J/cm^2.[4] The reason for this dose dependence of the activation of implanted Se is not clear at present and is being investigated.

5.0 CONCLUSIONS AND FUTURE PLANS

Experiments conducted have shown the capability of a pulsed electron beam to anneal the damage produced by implantation in semi-insulating GaAs. From the point of view of surface morphology, electron beam irradiated samples appear to be much more uniform than the ruby laser irradiated samples. The pulsed electron beam irradiated samples show a definitive damage energy density threshold in semi-insulating GaAs, beyond which considerable damage to the surface is observed. This damage energy density threshold is found to be dependent on the implantation dose. A similar damage energy density threshold was not observed in the ruby laser irradiated samples, possibly because of the beam non-uniformities involved. Better electrical activation of $10^{15}/cm^2$ 300 keV Se implants was achieved in the electron beam annealed samples compared to the laser annealed samples. The reason for low or poor activation of Se ions in the low-dose ($<10^{14}/cm^2$) implanted samples is still not clear.

Because of the encouraging results obtained from the electron beam annealing experiments, parallel annealing experiments will be carried out in the future with both pulsed laser and electron beam irradiation. Investigations will conform generally to the plans outlined in the first quarterly report. New experiments will hopefully provide an explanation as to the reason why the low dose implants ($<10^{14}/cm^2$) in semi-insulating GaAs show poor or no activation after irradiation with the ruby laser or the electron beam pulses.

6.0 REFERENCES

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