CHARACTERIZATION OF LASER ANNEALED SE-IMPLANTED GaAs

A. H. ORABY*

SUMMARY: A Q-switched ruby or Nd: Glass laser has been used to anneal Se-implanted GaAs. Differential Hall-effect and sheet-resistivity measurements have been carried out to investigate the electrical properties of the implanted layers as a function of laser energy density and laser wavelength. Electron concentrations greater than $1x10^{19}/cm^3$ were obtained but mobility values were low. Significant indifussion of Se atoms was observed following laser irradiation. The depth of electrically active layer greatly depends on the laser energy density. A comparison of the measured annealed depth as a function of laser energy density with the theoretically calculated annealed depth is presented.

Key Words: Laser, Laser annealing.

INTRODUCTION

Since the pioneering work of laser annealing (1-3) of ion implantation damage in silicon and galium arsenide, there have been a rapidly growing effort devoted to use laser annealing for the removal of implantation damage and the activation of implanted species in GaAs and other semiconductors (4-8). Pulse laser annealing is a very attractive processing technique for GaAs and other semiconductors as a means of capless annealing. However, there are problems in the pulsed laser annealing of GaAs, such as the lack of activation in low dose implanted GaAs and low mobilities in high dose implanted samples (9-11).

The efficiency of the laser annealing depends mainly on the absorption coefficient, which in turn depends on the wavelength and the material structure. Two different models have been suggested to explain pulsed laser annealing. The first model deals with a thermal transport model to describe the melting and resolidification of semiconductors (12-17). The other model supposes that pulsed laser annealing is primarily a nonthermal effect, resulting from formation of a dense electron-hole plasma (18).

*From Department of Physics, Faculty of Science, Mansoura University, Mansoura, Egypt.

In the present work, the dependence of pulsed laser annealing effects on the laser wavelength and energy density are investigated. Comparison of the electrical properties of the implanted GaAs between laser annealed and thermally annealed samples is represented. Comparison of experimental and theoretical melt depth produced by pulsed laser irradiation as a function of laser energy density are discussed.

EXPERIMENTAL PROCEDURE

Semi-insulating GaAs wafers of (100) orientation were implanted at room temperature with 60 keV Se ions at a dose of $1x10^{15}/cm^2$ in a non-channeling direction. Laser annealing was performed in air at room temperature with a Q-switched ruby laser (λ=0.694 μm) or Nd: Glass laser (λ=1.06 μm) with a single pulse of 20 nsec duration (FWHM) without using an encapsulant. The laser energy densities employed were 0.2-0.7 J/cm^2. A lapped quartz diffuser rod was used between the laser and the sample to obtain a homogeneous intensity distributon at the sample surface. For comparison purpose, some samples were thermally annealed in a flowing H_2 at 850°C for 20 min after encapsulation with approximately 1500-Å Si_3N_4 film.

Table 1: Sheet electron concentration (n_s), sheet mobility (μ_s) and the percentage of sheet electron concentration to the implantion dose (n_s/D) for 60 keV Se implanted GaAs at a dose of $1x10^{15}/cm^2$ and annealed at three different conditions.

Property	Thermal annealing 850°C/20 min	Laser annealing (0.6 J/cm^2)	
		Ruby laser	Nd: Glass laser
n_s	5 x 10^{13}	1.4 x 10^{14}	1.1 x 10^{14}
μ_s	1900	580	560
n_s/D%	5	14	11

Electron concentration and mobility profiles were obtained by differential Hall effect and sheet resistivity measurements combined with successive anodization and layer removal technique (19). Ohmic contacts were formed by deposited Au-Ge (12% Ge weight percent) dots. In the thermally - annealed samples, the contacts were alloyed for 2 min in flowing H_2. In the laser annealed samples, the contacts were formed by irradiating the back surface of the samples with a Q-switched Nd: Glass laser (20) at an energy density of 0.45 J/cm^2, since heat treatment above 200°C after laser annealing reduces the carrier concentration (21).

RESULT AND DISCUSSION

A comparative summary of the results of Hall-effect measurements made on Se-implanted GaAs, annealed at three different conditions is given in Table 1, where the values of sheet electron concentration n_s, electron mobility n_s and the percentage of sheet electron concentration to the implantation dose (n_s/D) are tabulated. The measurements were made after etching van der Pauw-type mesas provided with Au-Ge ohmic contacts (22). The data in Table 1 show comparable values of n_s, μ_s and the electrical activity (n_s/D) for both the samples annealed by the laser pulses of Ruby or Nd: Glass. The laser annealed samples showed higher values of n_s and lower values of μ_s than those obtained in thermally annealed sample. The relatively low values of μ_s for laser annealed samples is an indication of the presence of defects in these samples, even taking into account the high concentration of activated Se ions (8,9,11). The laser annealed samples showed a better electrical activity than the thermally annealed samples.

Table 2 shows the sheet electron concentration n_s, the electron mobility and the percentage of electrical activity (n_s/D) of 60 keV Se-implanted GaAs as a function of laser energy density and laser wavelengths. The data shows that the doping efficiency or the electrical activity increases with increases in laser energy density. As shown, pulsed ruby laser annealing gives better electrical activation values than pulsed Nd: Glass laser in Se-implanted GaAs. The electrical properties greatly depends on laser energy density. For

Table 2: Electrical properties of 60 keV Se-implanted GaAs at a dose of $1x10^{15}/cm^2$ and pulsed laser annealed by ruby or Nd: Glass laser and different energy densities.

Laser Energy (J/cm^2)	Ruby laser			Nd: Glass laser		
	n_s (cm^{-2})	μ_s (cm^2/V.s)	n_s/D%	n_s (cm^{-2})	μ_s (cm^2/Vs)	n_s/D%
0.3	1.2 x 10^{13}	390	1.2	9.2 x 10^{12}	400	0.92
0.4	5.5 x 10^{13}	420	5.5	3.2 x 10^{13}	430	3.2
0.5	9.5 x 10^{13}	480	9.5	6.5 x 10^{13}	510	6.5
0.6	1.4 x 10^{14}	580	14	1.1 x 10^{14}	560	11

samples annealed with laser energy density less than 0.2 J/cm^2, no activity of Se-implanted GaAs was obtained. The threshold energy density for electrical activation in both laser types was around 0.2 J/cm^2, but the electrical properties was poor at this energy. This indicates that this energy density was not enough to melt all of the entire amorphous layer, thus leading to polycrystalline regrowth on an underlying heavily damaged material (23). A visible surface damage was observed at an energy density greater than 0.65 J/cm^2. The results of Table 2 shows that Q-switched ruby laser is more effective than Q-switched Nd: Glass laser for annealing Se-implanted GaAs to obtain high electrical activation.

Figure 1 shows depth profiles of the electron concentration and mobility-measured on samples implanted with 60 keV Se ions at a dose of 1x10^{15}/cm^2 and laser annealed with Nd: Glass laser at three different energy densities. The Se atomic profile of the as-implanted sample predicted by LSS theory (24) is also plotted for comparison. The profiles show the diffusion (25) of Se atoms at laser energy densities of 0.5 and

Figure 1: Depth profiles of the electron concentration and mobility measured on samples implanted with 60 keV Se ions at a dose of 1 x 10^{15}/cm^2 and annealed at three different energy densities with Q-switched Nd: Glass laser.

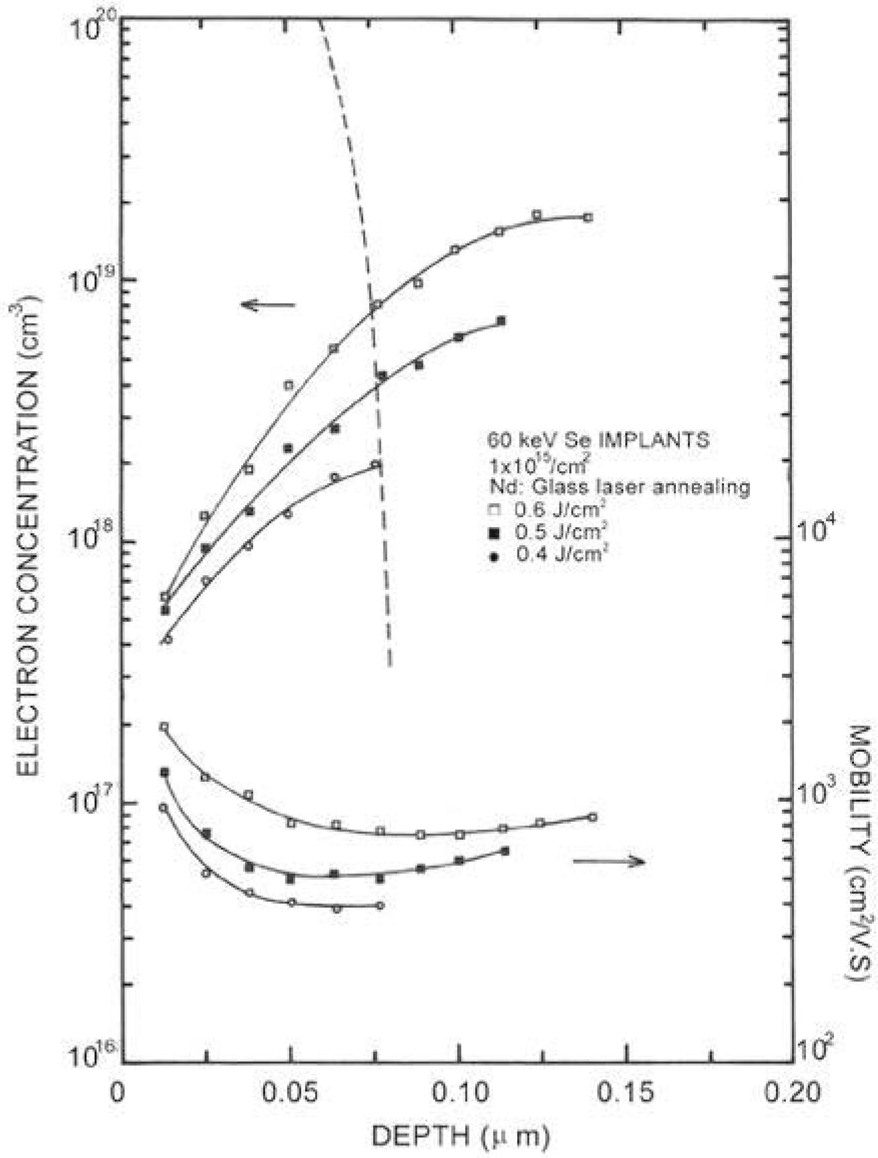
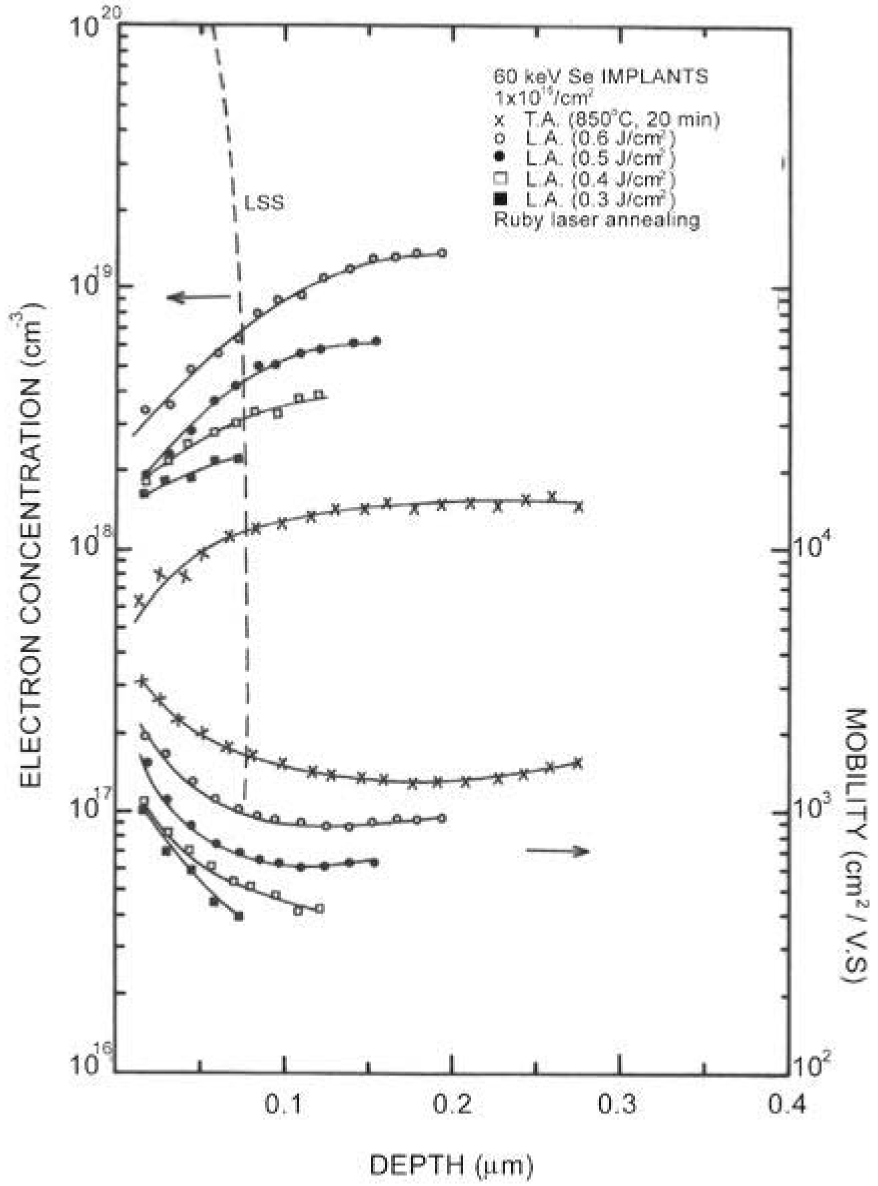


Figure 2: Depth profiles of the electron concentration and mobility measured on samples implanted with 60 keV Se ions at a dose of 1 x $10^{15}/cm^2$ and annealed Q-switched ruby laser at four different energy densities or thermally annealed.

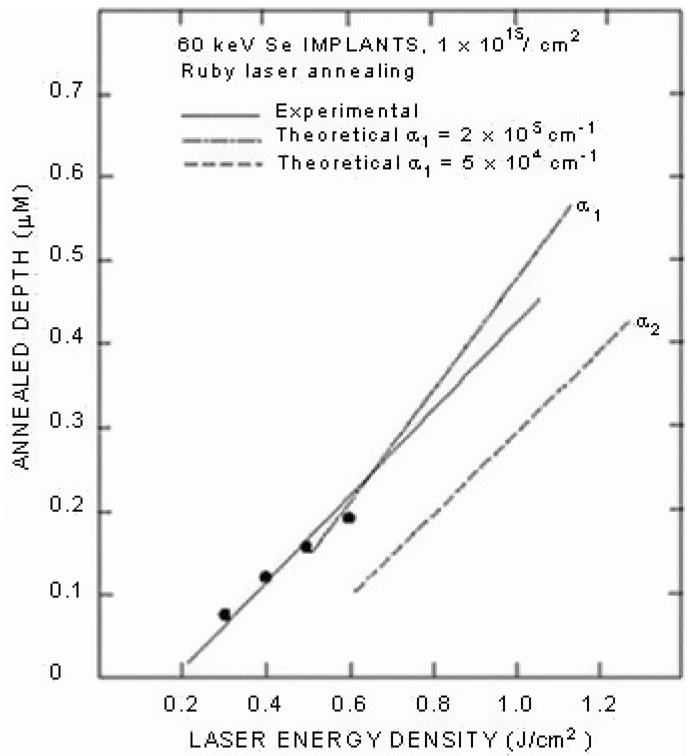


0.6 J/cm^2 compared with that predicted by LSS theory. For the sample annealed at an energy density of 0.4 J/cm^2, the highest electron concentration obtained was $1.9x10^{18}/cm^3$ with mobility of ~400 cm^2/V.s, whereas the electrically active layer extended to a depth of 800-Å from the surface. For sample annealed at an energy density of 0.6 J/cm^2, the highest electron concentration obtained was $1.8x10^{19}/cm^3$ with mobility of ~550cm^2/V.s., whereas the electrically active layer extended to a depth of 1400-Å from the surface. The profiles show that there is a less conductive layer near the surface which may be attributed to laser induced defects and in-diffussion of Se atoms. The electron concentration profiles shows a great dependence on the laser energy density, whereas the highest electron concentration was increased by approximately one order with increasing laser annealing energy density from 0.4 to 0.6 J/cm^2.

Figure 2 shows electron concentration and electron mobility profiles measured on samples implanted at a dose of $1x10^{15}/cm^2$ Se ions and annealed at four different laser energy densities of a pulsed ruby laser compared with the conventional thermal annealing. The LSS profile is ploted for comparison. For a sample, thermally annealed at 850°C for 20 min, the highest electron concentration is $1.5x10^{18}/cm^3$ with mobility $1400cm^2$/V.s, and the measured electron concentration profiles are deeper than the prediction of Se penetration based on LSS range theory. This penetration seems to be due to significant diffusion (25,26) of Se-implanted ions. For samples subjected to pulsed ruby laser irradiation at different energy densities, both electron concentration and electron mobility profiles show a great dependence on the laser energy density. For samples annealed with 0.6 J/cm^2 a high electron concentration is obtained of $1.4x10^{19}/cm^3$ which exceeds that of the thermally annealed samples by about one order. After laser annealing, the electron concentration profile shows a peak shift from the surface deeper than the depth predicted by LSS theory. This behaviour of Se in GaAs has been reported in plused laser annealing (27-28). This shift may be due to the effect of laser induced defects near the surface region which partially decreases the electron concentration near the surface and is also due to the redistribution of implanted Se in GaAs.

Figure 3 shows the experimental and theoretical values of the annealed depth as a function of ruby laser energy density for 60 keV SE-implanted GaAs at a dose of $1x10^{15}/cm^2$. Each point in the experimental data represents the thickness from the surface of the last possible measurements before reaching high resistance material with respect to the laser energy density employed. The position of these points from the surface are considered to be equal the depth of the melted layer that depends on the laser energy density. These points lie in a straight (solid line) intercept with the laser energy axis around the value of 0.18 J/cm^2. This value of energy density represents the threshold energy density for melting the surface of the implanted layer. This value is in agreement with Rutherford backscattering measurements (8,29), that shows no change in the crystal quality from that of the as-implanted sample for laser energy density less than 0.2

Figure 3: Experimental and theoretical values of the annealed depth as a function of laser energy density for 60 keV Se-implanted GaAs at a dose of 1 x $10^{15}/cm^2$.



J/cm^2. The theoretical (dashed lines) melted depth as a function of laser energy density was obtained from the reported data of Wang *et al.* (14). The calculation was based on the thermal melting model of pulsed ruby laser annealing of GaAs. The variation of the annealed depth (melted depth) with the laser energy density and the absorption coefficient is plotted for the purpose of comparison with the experimental data which shows some agreements with the theoretical calculation based on the value of the absorption coefficient α_1=2x10^5 cm^{-1}.

CONCLUSIONS

The effects of pulsed laser annealing on the electrical properties of Se-implanted GaAs as a function of laser energy density and laser wavelength were investigated by means of differential Hall effect measurements. Laser annealing of the sample implanted at a dose of 10^{15}/cm^2 yielded an electron concentration higher than that obtained by thermal annealing and a lower electron mobility than that expected in uncompensated bulk GaAs. Electrical properties of Se-implanted GaAs greatly dendes on laser energy density. There is a threshold laser energy density for the recovery of implantation damage and electrical activation of the implanted ions. The laser annealing energy density should be enough to melt the entire implanted layer.

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Correspondence:
A. H. ORABY
Department of Physics,
Faculty of Science,
Mansoura University,
Mansoura, EGYPT.