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Low Energy Focused Ion Beam System and Application to Low Damage Microprocess

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We have developed a low energy focused ion beam (FIB) system by employing retarding field optics. The system is equipped with a gas jet and is used for ion beam assisted etching or deposition. To evaluate the usefulness of low energy FIB, we have been investigating defects in GaAs induced by irradiation of low energy Ga^+ FIB and Ar^+ unfocused beams. Defets induced by irradiation at 300 K were observed even at a depth of >2000 Å, which is much deeper than the ion range. However, it was observed that the deep distribution was suppressed by irradiation at low temperature (100 K.

KEYWORDS: low energy focused ion beam, retarding field optics, low damage process, GaAs, diffusion of traps, low temperature irradiation

§1. Introduction

Focused ion beam (FIB) technology is useful for various semiconductor processes such as maskless doping, ion beam lithography, ion beam assisted etching and deposition.[1-5] For doping and ion beam lithography, a high energy beam is required to dope thick layers or to expose a thick resist. However, for etching, deposition, and shallow doping, low energy FIB is preferable to reduce radiation damage.[6] A previous experiment on ion beam etching of GaAs indicates that defects are significantly reduced by ion beam assisted etching using 500 eV beams.[7]Also reported was that ion beam assisted or reactive ion beam etching induces much less damage compared to physical sputter etching.[8] Therefore, it is useful to develop a low energy FIB system which can be used for ion beam assisted etching and deposition to reduce radiation damage in the substrate.

Retarding field optics has the possibility to produce a finely focused ion beam with the landing energy of less than 1 keV.[9,10] The previous systems formed low energy FIB by applying a retarding field between the lens electrode and the target; i.e., the target is used as part of a focusing lens electrode. With the arrangement, it is impossible to install a gas jet for ion beam assisted etching (IBAE) and deposition because the gas jet disturbs axisymmetric retarding field.

We designed an electro static lens for retarding optics without using the target as a lens electrode and built an experimental column. The simulated optical property of the present system was confirmed experimentally.

We studied the characteristics of the damages in GaAs induced by low energy Ga^+ FIB irradiations by measuring the defect concentration and distribution profiles using deep level transient spectroscopy (DLTS) and the bias modulation differential C-V method. The effect of irradiation temperature was also measured.

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§2. Low Energy FIB System

The present low enervy FIB system is schematically shown in Fig. 1. This system employs retarding field optics and is composed of a retarding electrode and a sub-electrode in addition to an immersion objective lens. The sub-electrode controls the electric field between the immersion objective lens and retarding electrode. Both the reatrding electrode and the trarget are biased at almost the same positive high potential V_b to obtain a field-free region between them. This allows the installment of micro channel plate (MCP) for detecting the secondary electron image and of a gas jet near the target for ion

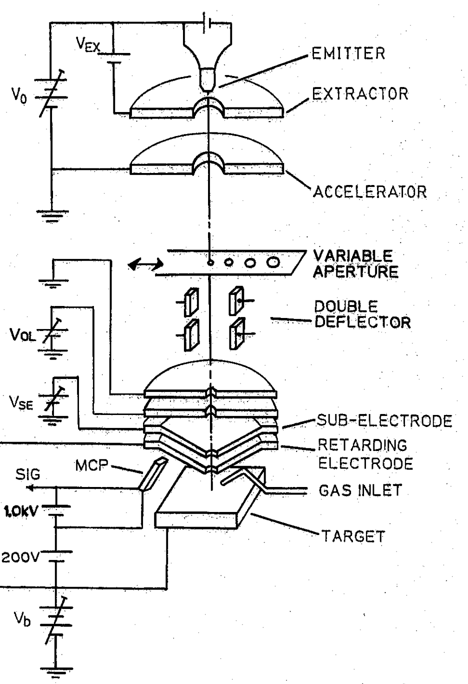

Fig. 1. Schematic representation of the optical column of the low energy FIB sytem.

beam assisted etching and deposition. To increase the secondary electron collection efficiency of MCP, the retarding electrode is biased at several voltages lower than that of the trarget. By applying this bisa voltage, the fraction of secondary electrons which escape through the center hole of the retarding electrode is suppressed. Double-deflection effectively improves the transverse chromatic aberration and reduces the change of magnification by changing the retarding potential.[11)]

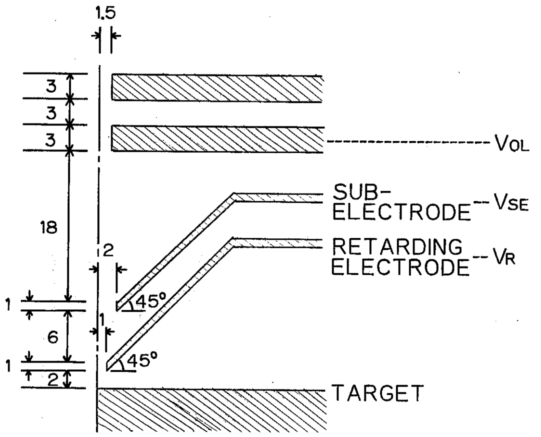

Fig. 2. The dimensions of the lens for retarding optics.

Table I. Computed aberration coefficients of the optical column. C_c: Chromatic aberration coefficient, C_s: Spherical aberration coefficient, M: Magnification.

	Landing energy (keV)	C_c (mm)	C_s (mm)	M
With retarding	0.5	2.6	21	0.17
	1.0	4.5	260	0.24
	10.0	51.7	1900	0.17
Without retarding	15.0	74.3	2400	0.15

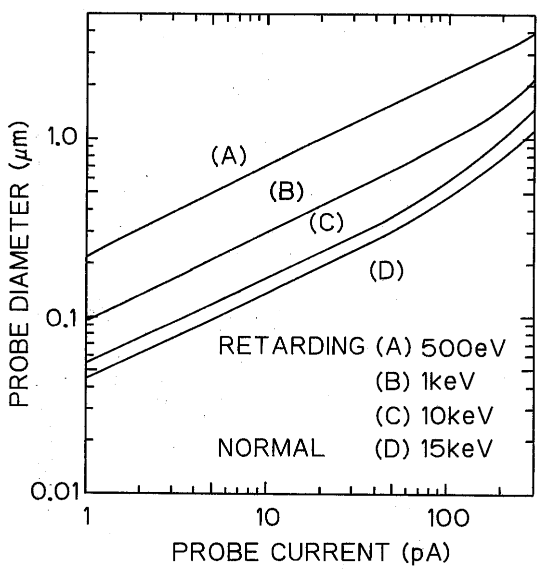

Fig. 3. Focusing characteristics of the low energy FIB system. The simulated final probe diameter is plotted as a function of final probe current. A primary veam energy of 15 keV is assumed.

Aberration coefficients and probe characteristics calculated using the programs developed by Munro are shown in Table I and Fig. 3, respectively. The electrode configuration is shown in Fig. 2. The distance from the objective to the upper electrode of the immersion lens is 183 mm. We assumed that the acceleration voltage is 15 kV, the energy spread of the beam is 10 eV, the source angular current density is 20 μA/str, the source diameter is 50 nm, and the extracting voltage is 4.2 kV. We can expect a submicron probe diameter at the landing energy lower than 1 keV by the present system. Experimentally, we obtained 1 keV Ga^+ FIB with a probe diameter of 2.5 μm, and a current of 300 pA. This result is almost comparable with the calculated values. At a low probe current, observation of the secondary electron image was difficult because of the detection limit of the MCP and the formation of submicron beam was unable to confirm.

§3. Damages in Low Energy Ion Beam Processed GaAs

We investigated ion beam irradiation induced damage in order to demonstrate the usefulness of low energy ion beam processes. The samples used were Si-doped, HB grown, (100) oriented GaAs with a carrier concentration of around 10^{17} cm^{-3}. Low energy Ga^+ FIB irradiation was performed at the landing energy of 100 eV at room temperature. After the irradiation, the samples were annealed at 400 or 600°C for 10 min in a flowing pure hydrogen atmosphere. To investigate the effect of irradiation temperature, 500 eV unfocused Ar^+ irradiation was also performed at target temperature of 100 and 300 K. The Ar^+ beam current density was 10 μA/cm^2. After the irradiation, Al Schottky contacts with a diameter of 550 μm were formed on the irradiated surface, and Au–Ge ohmic contacts on the backside of the wafers. DLTS measurement was carried out at a temperature between 100 and 400 K, with a rate window ranging from 11 to 139 s^{-1}. The shallow level concentration which was used for estimating the trap concentration was measured using the C-V method.

The DLTS spectra of the samples irradiated by 100 eV Ga^+ FIB at a dose of 5×10^{15}/cm^2 are shown in Fig. 4. In the virgin sample, EL-2 and EL-6, which are typical grown-in defects in HB grown GaAs, were observed. Two new trap centers labeled L-1 and L-2 were observed in a as-irradiated sample at temperatures of 180 and 290 K, respectively. Traps L-1 and L-2 have activation energies of 0.31 and 0.52 eV. After the annealing at 400°C for 10 min, the density of trap L-1 decreased and a new trap (labeled L-3) which was not observed in the as-irradiated sample and has activation energy of 0.32 eV was observed around 200 K. With annealing at 600°C, only the electron trap EL-2 was observed at the deeper region from the surface, as shown by the solid line. However, trap L-2 was observed near the surface, as shown by the broken curve.

Figure 5 shows the distraibution profile of the dominant electron trap L-2 observed for samples which were ir-

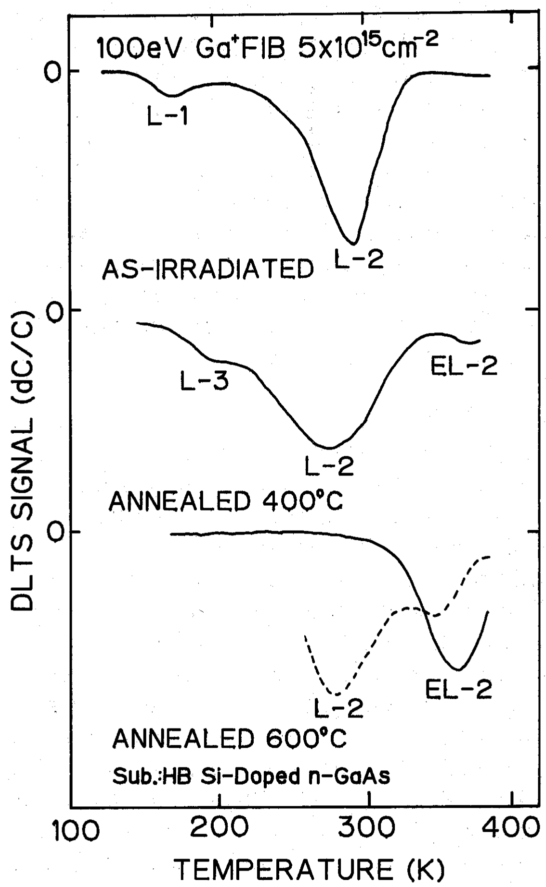

Fig. 4. The DLTS spectra of the sample irradiated by 100 eV Ga^+ FIB. The broken line is the signal at the depth of about 300 Å and the solid line is that of 700 Å.

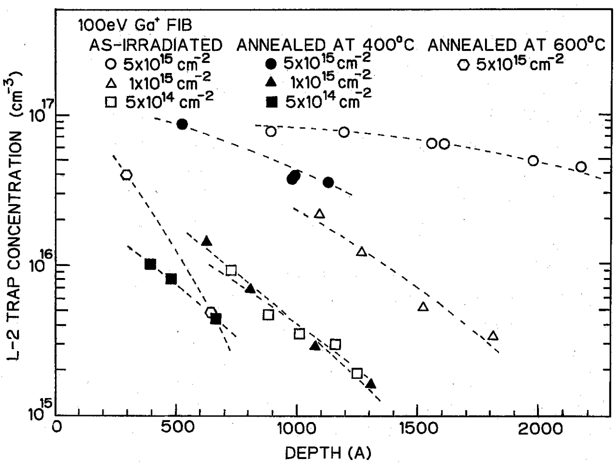

Fig. 5. The distribution profile of trap L-2 in GaAs irradiated by 100 eV Ga^+ FIB.

radiated at various doses using 100 eV Ga^+ FIB and annealed at 400 or 600°C. We determined the distribution profiles of the traps using DLTS by varying a filling bias pulse height. Annealing at 600°C reduced significantly the trap concentration of L-2. For the dose lower than $1\times10^{15}/cm^2$, trap L-2 decreased below the detection limit ($<10^{15}/cm^3$) and only EL-2 was observed. At a dose of $5\times10^{15}/cm^2$, trap L-2 was still observed at a depth shallower than 700 Å after annealing at 600°C. An annealing temperature of higher than 600°C is required for full recovery. The damage reduction in the presence of Cl_2 in IBAE was reported previously.[12] These results indicate the possibility of irradiating GaAs at a dose above $1\times10^{15}/cm^2$ with low damage in IBAE. The L-2 center distributes at a depth deeper than 200 Å. The projected range of 100 eV Ga^+ in GaAs is only a few 10's Å. Therefore, it is likely that the L-2 center diffuses during the ion irradiation. To reveal the effect of diffusion, Ar^+ ion irradiation at low temperature was performed.

Figure 6 shows the DLTS spectra of the sample irradiated by 500 eV Ar^+ at a dose of $3\times10^{15}/cm^2$, and at temeperatures of 100 and 300 K. The spectra of the sample irradiated at 100 and 300 K were similar to each other, and trap ceters labeled L-4 and L-5 were observed in both cases.

Figure 7 shows the Arrahenius plots for traps L-4 and L-5. Plots for the EL-12 and EB-4 levels which were previously reported[13] are also shown by the broken lines for comparison. Activation energies for trap L-4 and L-5 are 0.72 and 0.42 eV, respectively. Traps L-4 and L-5 were also observed in GaAs irradiated by low energy Ga^+ ions at a low dose of below $1\times10^{15}/cm^2$. However, the concentrations of these traps were much smaller than that of trap L-2 and were masked by trap L-2 at high dose.

Distribution profiles of traps L-4 and L-5 in the samples irradiated at 300 and 100 K are shown in Fig. 8. The defects again distribute much deeper than the pro-

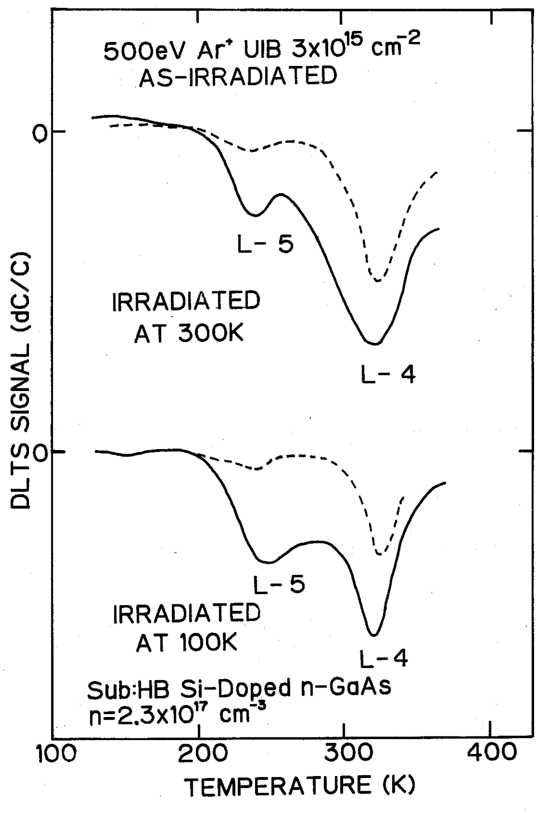

Fig. 6. The DLTS spectra of the sample irradiated by 500 eV Ar^+ ions. The broken line shows a deeper region than the solid line.

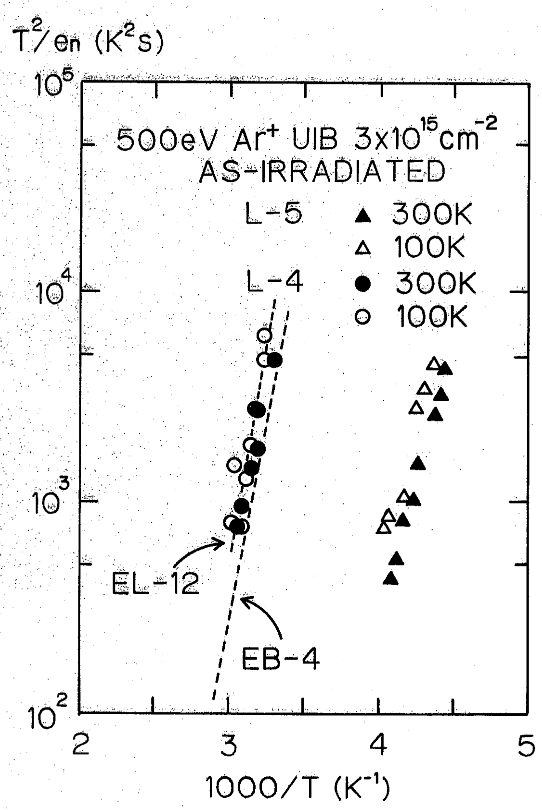

Fig. 7. Arrhenius plot for traps L-4 and L-5 in GaAs irradiated by 500 eV Ar^+ ions at 100 or 300 K.

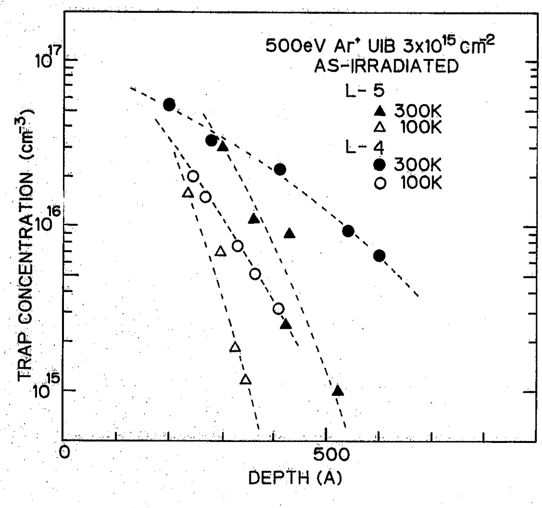

Fig. 8. The distribution profiles of traps L-4 and L-5 in GaAs irradiated by 500 eV Ar^+ ions at 100 or 300 K.

Table II. Diffusion constants of traps L-4 and L-5 in GaAs irradiated by 500 eV Ar^+.

Irradiation temperature (K)	L-4 diffusion constant (cm^2/s)	L-5 diffusion constant (cm^2/s)
300	2×10^{-13}	5×10^{-14}
100	6×10^{-14}	3×10^{-14}

jected range of the ion and the distribution profile depends on the temperature; it is shallower for the low temperature irradiation. The distribution profiles of traps L-4 and L-5 were stable at the temperature of less than 400 K. These results indicate that diffusion of defects takes place during the irradiation.[14,15] The diffusion constants were estimated by fitting the observed profiles and are an order of 10^{-13} cm^2/s, as shown in Table II. The fitting was performed by using Gaussian profiles. The details of mobile defects are unknown, but should be simple defects like divacancies or interstitials because these are thought to be movable at low temperature.

§4. Conclusions

We build a low energy FIB system by employing retarding field optics. The present FIB sytem produces a finely focused ion beam at an energy of below 1 keV. It was observed that the defect density induced in GaAs can be reduced by using a low energy ion beam, but some defects distribute much deeper than the ion range. The diffusion of the defect occurred during the irradiation. To suppress deep distribution, it may be useful to irradiate at a low temperature. It was found that defects are reduced to below detection limit ($<10^{15}/cm^3$) by annealing at 600°C for the dose lower than $1\times10^{15}/cm^2$.

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