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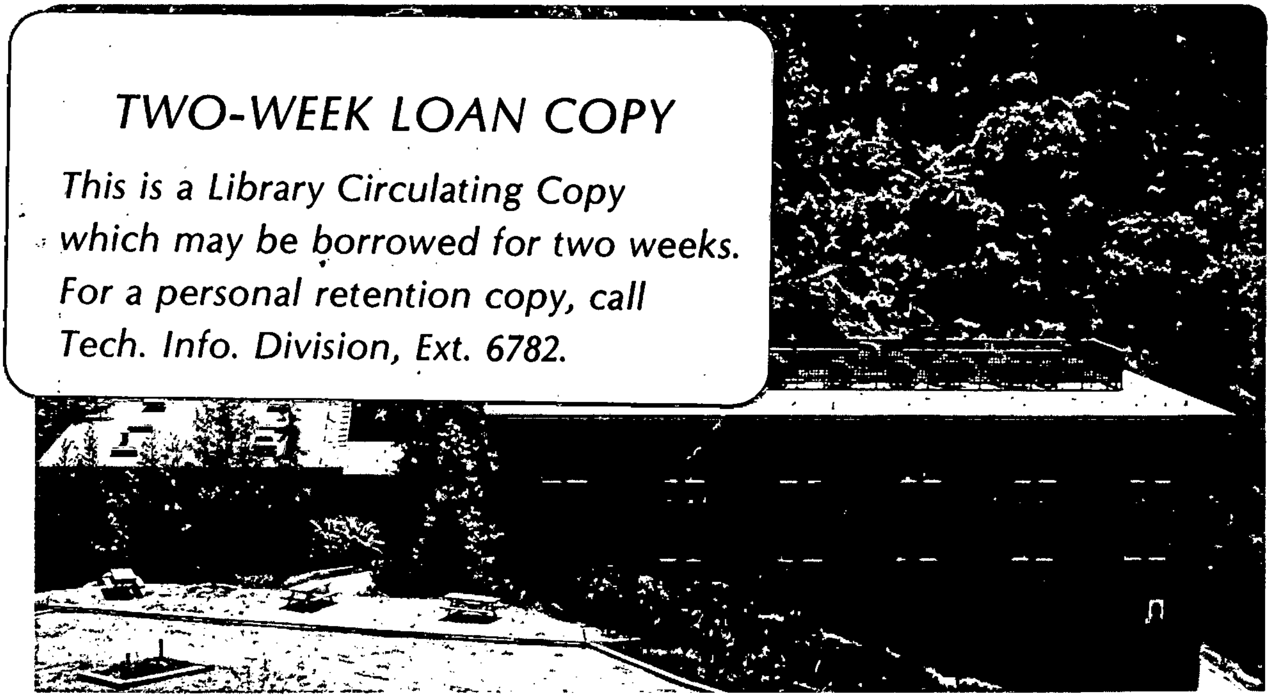

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Pulsed Electron Beam Induced Recrystallization and Damage in GaAs

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ABSTRACT

Single-pulse electron-beam irradiations of 300 KeV 10^{15} Kr^+/cm^2 or 300 KeV $3x10^{12}$ Se^+/cm^2 implanted layers in unencapsulated <100> GaAs are studied as a function of the electron beam fluence. The electron beam pulse had a mean electron energy of ≈20 KeV and a time duration of $\approx 10^{-7}$s. Analyses by means of MeV He^+ channeling, optical microscopy and TEM show the existence of narrow fluence window (0.4-0.7 J/cm^2) within which amorphous layers can be successfully recrystallized, presumably in the liquid phase regime. Too high a fluence produces extensive deep damage and loss of As.

Thermal annealing of GaAs to remove heavy ion implantation damage and to electrically activate dopants is typically done at temperatures >800°C. In order to prevent escape of As and precipitation of Ga, the GaAs surface must be protected by an inert encapsulant such as Si_3N_4 or SiO_2. However, no one encapsulant is suitable for all processes.[1] Another approach is to provide a suitable ambient pressure of As and Ga during annealing, but this method has not yet been fully optimized.[2] An attractive alternative is to use transient annealing as in the case of Si.[3] Several recent studies[4-7] have indicated that laser annealing can indeed be used for removing damage in implanted amorphous GaAs layers, and for placing the implanted species into substitutional sites. The use of a pulsed electron beam to achieve comparable results has recently been reported.[8] For a 300 keV, $10^{15}Se^+/cm^2$ implantation, the measured free electron concentration achieved by transient annealing was higher than that obtained after furnance annealing, but the mobility was lower. Low dose ($<10^{14}sec^+/cm^2$) implantations, however, did not show any measurable electrical activity after transient annealing. This paper compares the results of pulsed electron beam irradiation of high dose and low dose implanted layers in GaAs. The layers were characterized by He^+ Rutherford backscattering/channeling spectrometry, optical microscopy and transmission electron microscopy (TEM).

Semi-insulating, Cr-doped GaAs samples of <100> orientation were implanted at room temperature with 300 keV Kr^+ ions to a (high) dose of $10^{15}cm^{-2}$, or with 300 keV Se^+ ions to a (low) dose of $3x10^{12}cm^{-2}$. The <100> axis of the samples was offset by ∿7° with respect to the beam during implantation. The unencapsulated samples were irradiated with a pulsed electron beam in vacuum (Spire Corp., Bedford, MA 01730). The mean electron energy was ∿20 keV, and the pulse duration was $\sim 10^{-7}s$.[9] Channeling measurements were taken by using a 2.4 MeV He^+ beam incident on samples over areas typically 1mm x x 2mm. TEM studies were performed on the same samples in "plan" view.

Results of channeling analysis, optical microscopy and TEM are given in Figs. 1 to 6. The unirradiated, high dose Kr^+ implanted sample had a 2200Å thick amporphous surface layer (Fig. 1~~a~~). The As/Ga ratio at the surface, obtained from the random backscattering spectrum, was close to unity, and the surface was optically featureless (Fig. 2). TEM plan view showed the damage as a featureless structure (Fig. 3), and the transmission electron diffraction (TED) pattern confirmed the existence of the amorphous layer (Fig. 3). After a pulsed electron irradiation of 0.4 J/cm^2, the aligned spectrum was the same as before irradiation (Fig. 1), and the surface remained optically clean (Fig. 2). However, TEM results showed that the layer now had a grainy structure with mean grain size ∿1000Å (Fig. 3). The TED pattern indicated the existence of a polycrystalline layer (Fig. 3). After a 0.7 J/cm^2 irradiation, the channeling yield at the surface, χ_0, had dropped from 1.00 and 0.11 (Fig. 1), indicating rather good crystalline quality. Comparsion with the aligned spectrum for a virgin crystal (i.e., unimplanted and unirradiated), for which $\chi_0 = 0.04$ in the set-up used in this work, showed that some disorder was present after a 0.7 J/cm^2 pulse. The surface of the irradiated sample was found to be Ga rich (As/Ga ≃0.8). Optical microscopy (Fig. 2) showed the incipient formation of faint surface blemishes and TEM (Fig. 3) indicated the existence of dislocation lines and gray patches in the regrown layer. TED indicated that the layer was now a single crystal (Fig. 3). At a still higher electron fluence of 1.1 J/cm^2, the surface channeling yield was 0.17, and a higher dechanneling rate indicated the presence of extended defects down to a depth greater than 1μm. The As/Ga ratio at the surface was ≃0.8. Optical microscopy revealed defects at the surface that had definitive geometrical patterns superimposed with microcracks (Fig. 2). TEM showed a high density of dislocations and the presence of microcracks. TED indicated the material was still a single crystal. To summarize the observations of electron beam pulsed annealing of high dose ($10^{15}cm^{-2}$) Kr^+ implanted in GaAs, it was noted that at low energy density (0.4 J/cm^2), the recrystallization of the amorphous layer gave rise to the formation of polycrystalline material. Electron irradiation pulsing of 0.7 J/cm^2 or higher resulted in single crystalline layers with increasingly higher density of dislocations. The optimum energy density for successful recrystallization seems to lie between 0.4 and 0.7 J/cm^2 for the pulsed electron beam parameters chosen.

Figures 4 to 6 show the results of measurements performed on the low dose ($3x10^{12}cm^{-2}$) Se^+ implanted and pulsed electron beam irradiation samples. Both the unirradiated and the 0.4 J/cm^2 irradiated samples exhibited a χ_o value of 0.05, almost as good as a perfect single crystal (Fig. 4). The surfaces were optically featureless (Fig. 5), and the surface composition was stoichiometric. However, TEM examination (Fig. 6) of the 0.4 J/cm^2 irradiated sample revealed the existence of disordered zones (gray patches) with some probable Ga precipitates (black dots).[10] After a 0.7 J/cm^2 pulse irradiation, χ_o, increased to 0.07, the channeled spectrum was found to be well above that for the unirradiated sample, and the surface As/Ga was 0.75. Optical inspection (Fig. 5) showed the presence of defects on the surface of <1μm diameter, with a density of 100-150/1000μm², forming hexagonal and other patterns. TEM analysis (Fig. 6) revealed Ga rich regions (black patches and dots) and the irradiated layer was found to possess dislocation lines and stacking faults. TED showed that the layer was still single crystalline. At an electron fluence of 1.1 J/cm^2, χ_o

reached 0.31 (Fig. 4), and the shape of the channeled spectrum indicated a heavily disordered structure. The As/Ga ratio at the surface was ≈0.7. Large, rectangular, 40x60μm surface cracks were seen under the microscope in addition to the same defects observed after 0.7 J/cm^2 irradiation (Fig. 5). These cracks, which were probably due to thermal stress produced by the rapid temperature change, occurred along the cleavage planes in the crystal. A TEM micrograph for this sample (Fig. 6) exhibited a dense dislocation network, probably arising from the same high thermal stresses that caused cracks in the crystal.

In summary, the recrystallization and annealing of implanted GaAs layers by a pulsed electron beam can be interpreted as occurring via liquid phase regrowth. A first evidence is by the existence of a threshold for the annealing of amorphous layers. For the electron beam parameters chosen, the annealing threshold lies between 0.4 and 0.7 J/cm^2 for a 2200Å amorphous layer created by a room temperature 300 KeV 10^{15}cm^{-2} Kr$^+$ implantation. Below the threshold, at 0.4 J/cm^2, it appears that the electron beam pulse induces melting of the amorphous layer, but the melt depth does not penetrate the entire 2200Å of the amorphous layer, thus leading to polycrystalline regrowth on an underlying heavily damaged layer. Above the threshold, melting of the entire amorphous layer takes place, leading to epitaxial regrowth on single crystalline substrate. These observations are in agreement with analogous studies performed on laser-annealed samples.[11-13] Crystalline (or slightly damaged) layers irradiated with an electron beam pulse of 0.4 J/cm^2 or higher possess lattice defects, and no measurable electrical activation of the implanted species (3×10^{12}Se$^+$/cm^2 in the present case) is observed, in contrast to capped thermal annealing where good activiation (⩾60%) is achieved.[14] It is interesting to note that electron beam pulsing at a fluence of

0.7 J/cm^2 produces more damage in the high dose, amorphous implanted layer than in the low dose case, as seen in the respective channeling spectra. This effect can be explained as follows. The absorption of energy deposited by the electron beam is not expected to depend significantly on the microstructure of the material. However, the thermal properties of the layers, namely the latent heat of fusion and the melting temperature, which control the melt depth and the duration for which the layer remains molten, may be different in the two cases. A similar dependence for electron beam irradiation of implanted layers in Si has been previously observed.[15] Amorphous or heavily damaged layers would have a lower heat of fusion than crystalline material. Thus, for equal electron beam fluence, an amorphous layer would melt deeper and stay molten longer than a crystalline layer. Observations indicate a significant loss of As at the surface after a 0.7 J/cm^2 pulse irradiation. Thus, as already pointed out by Tsu et. al.,[7] the regrowth would take place from a Ga-rich liquid, which may account for some of the disorder. These effects are even more pronounced for 1.1 J/cm^2 irradiations. It would appear that a judicious choice of electron beam parameters (such as fluence, pulse length, and energy distribution) could be found which would optimize the annealing process in GaAs.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1 Energy spectra of 2.4 MeV $^4He^+$ ions backscattered from <100> GaAs, implanted at room temperature with 300 KeV $10^{15}Kr^+/cm^2$, before and after single-pulse electron beam irradiations at the indicated fluences. The random spectrum is for the as-implanted (unirradiated) sample. The aligned spectrum from a virgin sample (unimplanted and unirradiated) is shown for comparison. The Kr signal is too small to be observed in all cases.

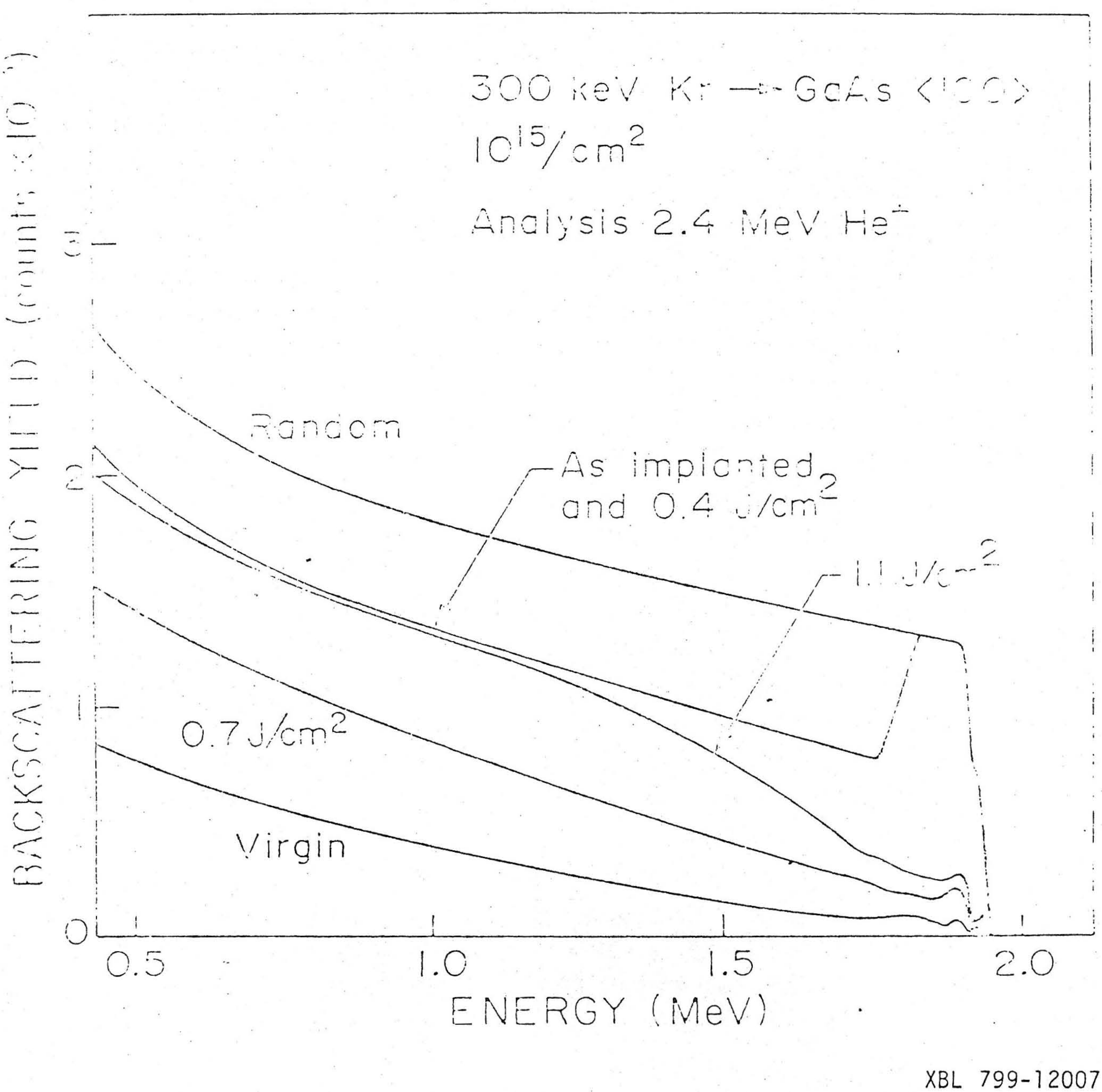
Fig. 2 Optical micrographs for the same samples as in Fig. 1.

Fig. 3 TEM Micrographs for the same samples as in Fig. 1.

Fig. 4 Energy spectra of 2.4 MeV $^4He^+$ ions backscattered from <100> Ga/As, implanted at room temperature with 300 KeV, $3x10^{12}$ Se^+/cm^2, before and after single-pulse electron beam irradiations at the indicated fluences. The random spectrum is for the as-implanted (unirradiated) sample. The spectrum for a virgin sample (unimplanted and unirradiated) cannot be distinguished from the one for the as-implanted sample on this scale. The Se signal is too small to be observed in all cases.

Fig. 5 Optical micrographs for the same samples as in Fig. 2.

Fig. 6 TEM micrographs for the same samples as in Fig. 2.

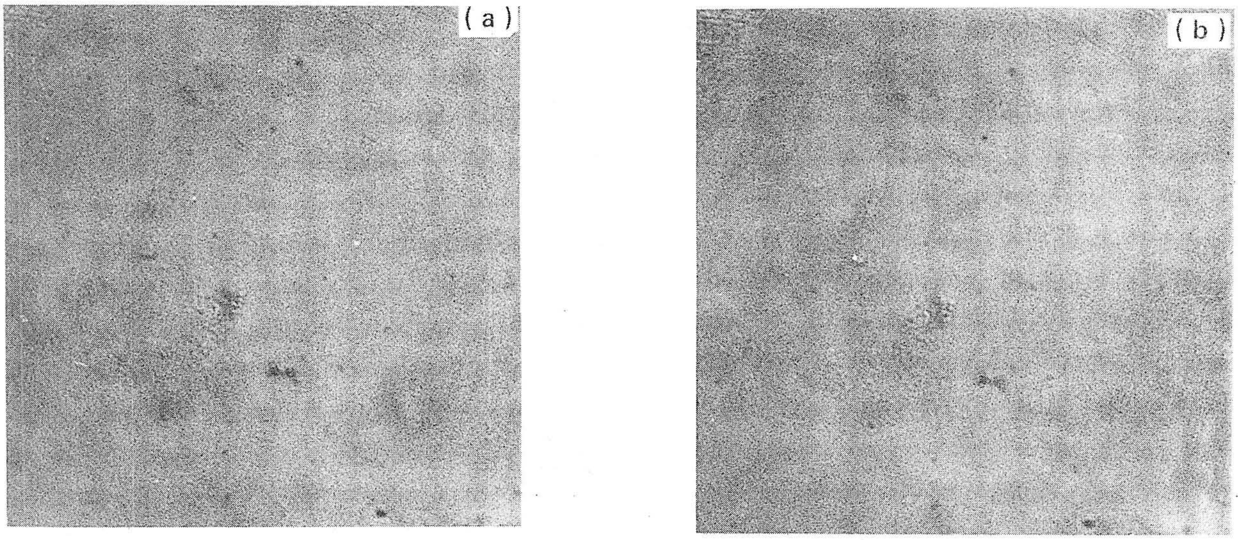


XBL 799-12007

Fig. 1

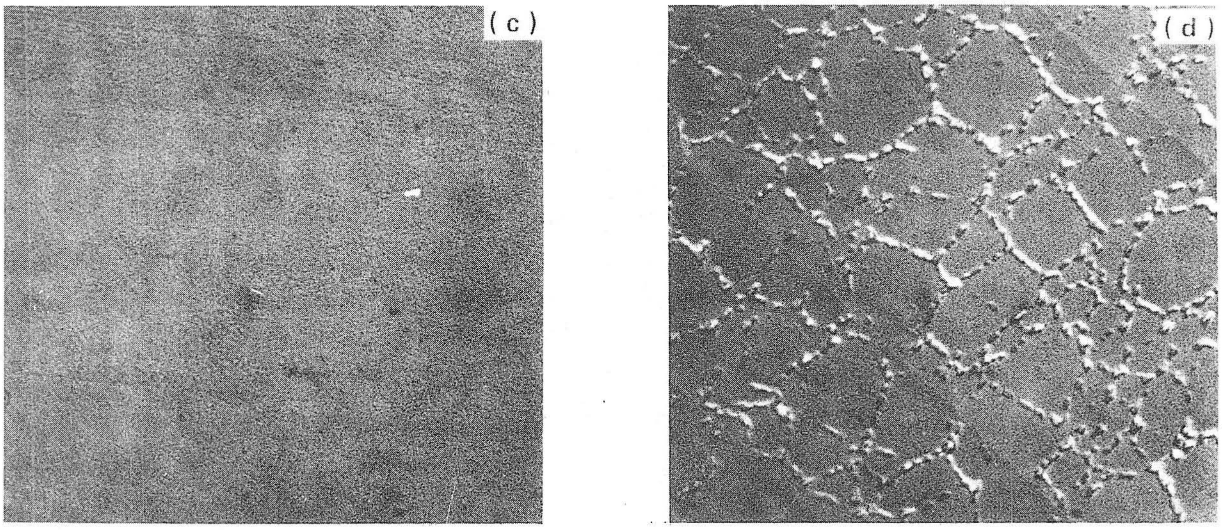
Kr → GaAs, R. T., 300 keV, 1 x 10^{15} cm^{-2} ELECTRON
BEAM ANNEAL, NO ENCAPSULANT

SC79-4284



NO ANNEAL

0.42 J/cm^2



0.67 J/cm^2

1.05 J/cm^2

20μm

XBB 799 11889

Fig. 2

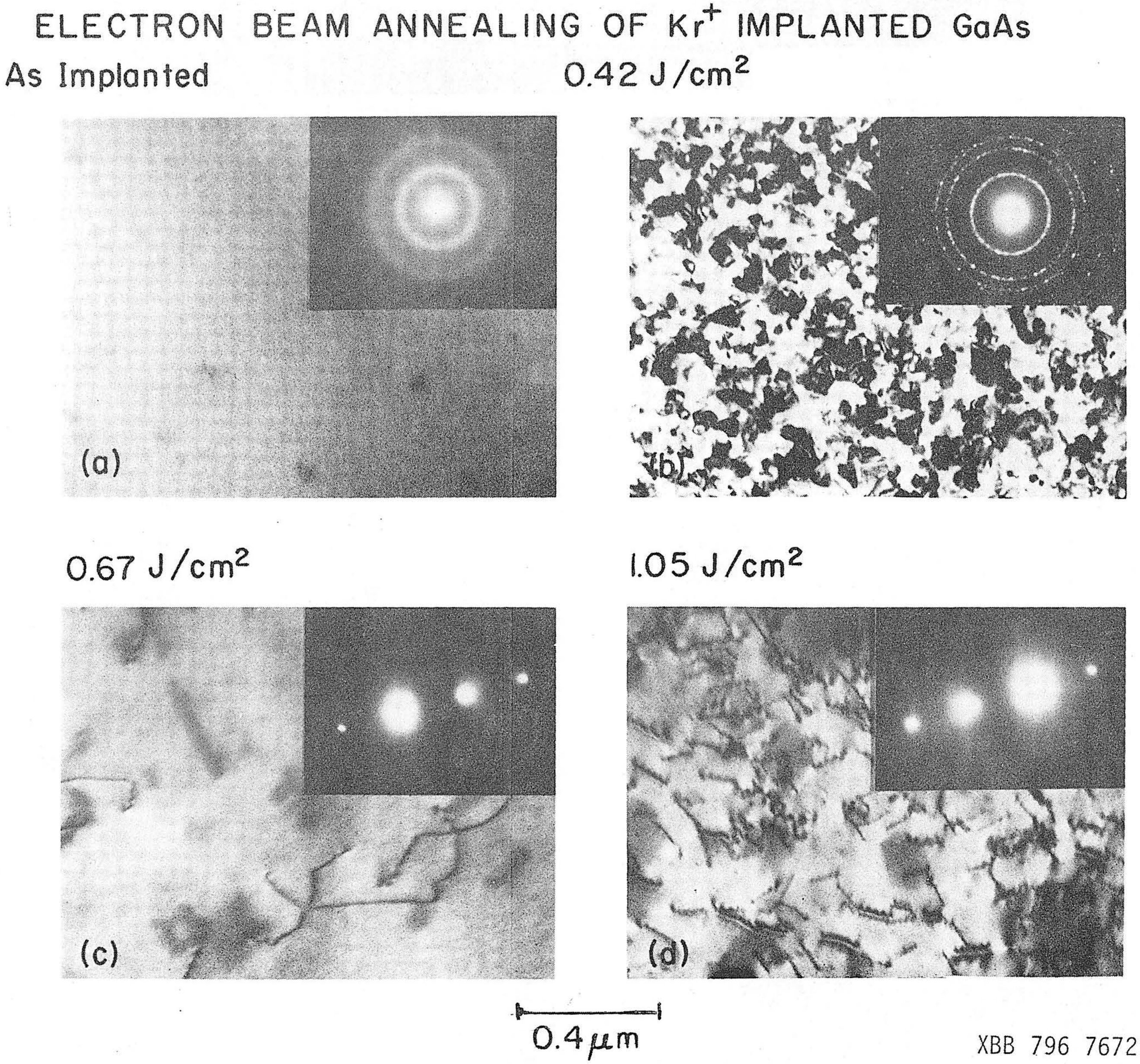
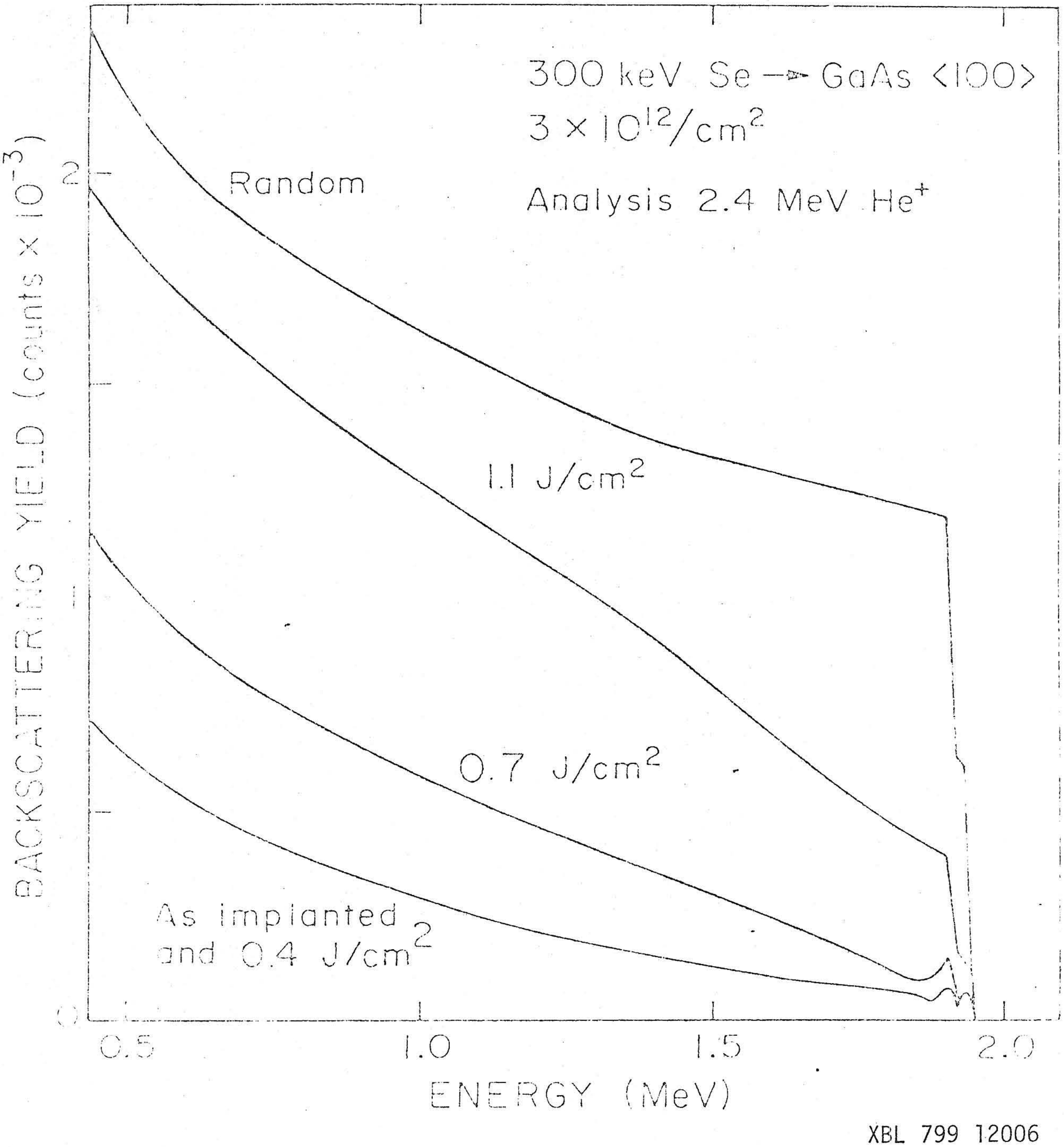
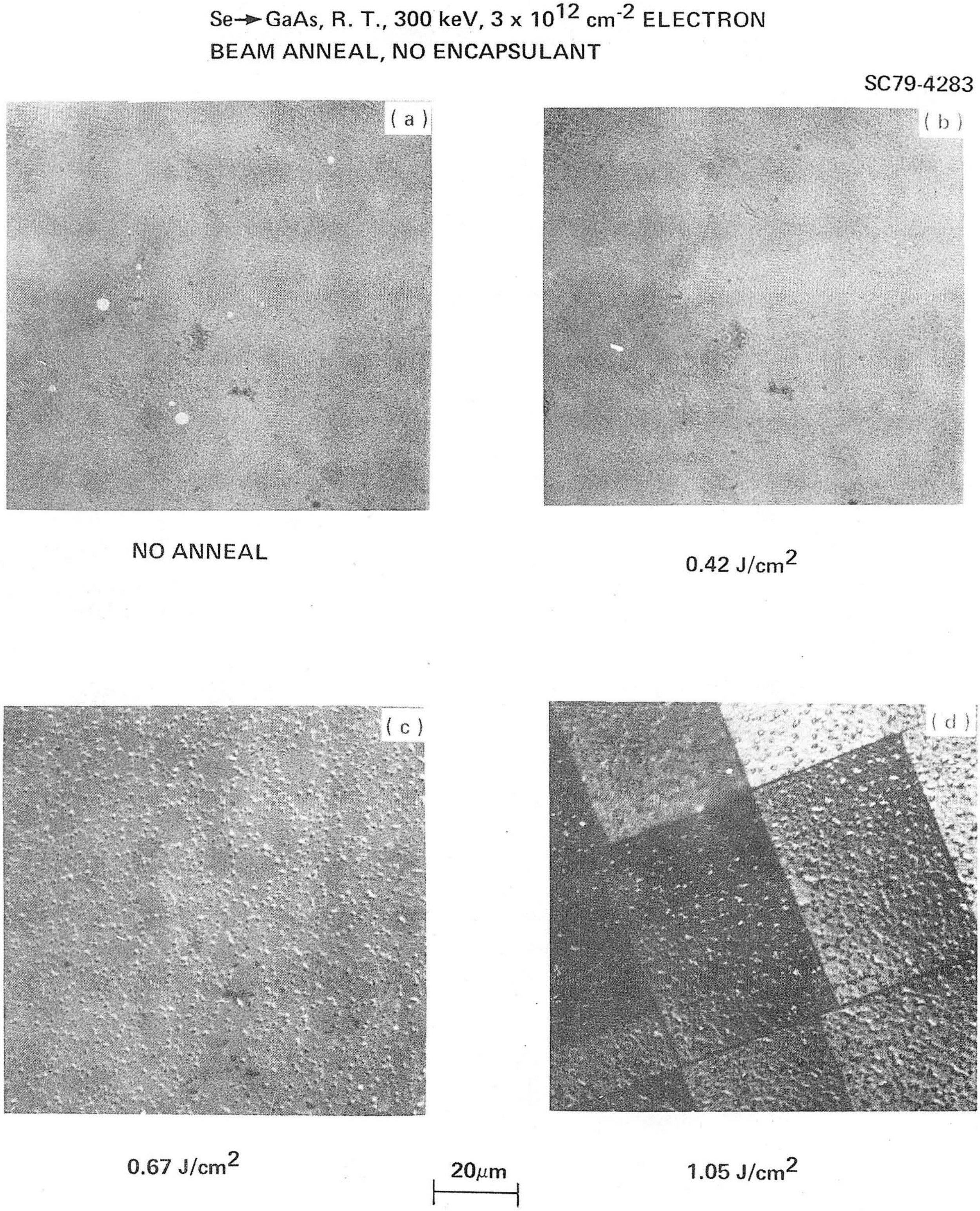

ELECTRON BEAM ANNEALING OF Kr+ IMPLANTED GaAs
As Implanted
0.42 J/cm2
(a)
(b)
0.67 J/cm2
1.05 J/cm2
(c)
(d)
0.4 μm
XBB 796 7672

Fig. 3



XBL 799 12006

Fig. 4



XBB 799 11890

Fig. 5

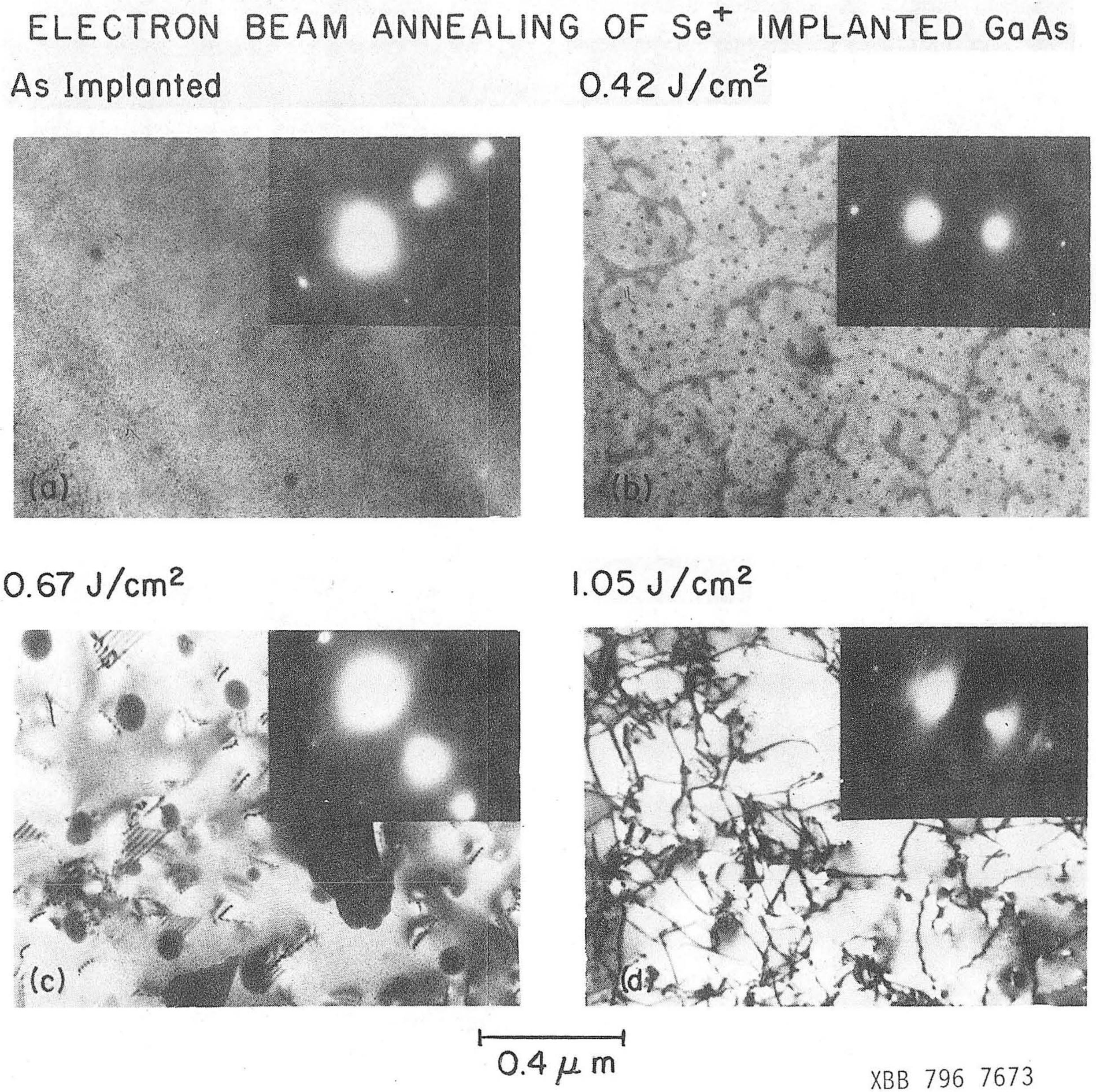


Fig. 6

XBB 796 7673

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