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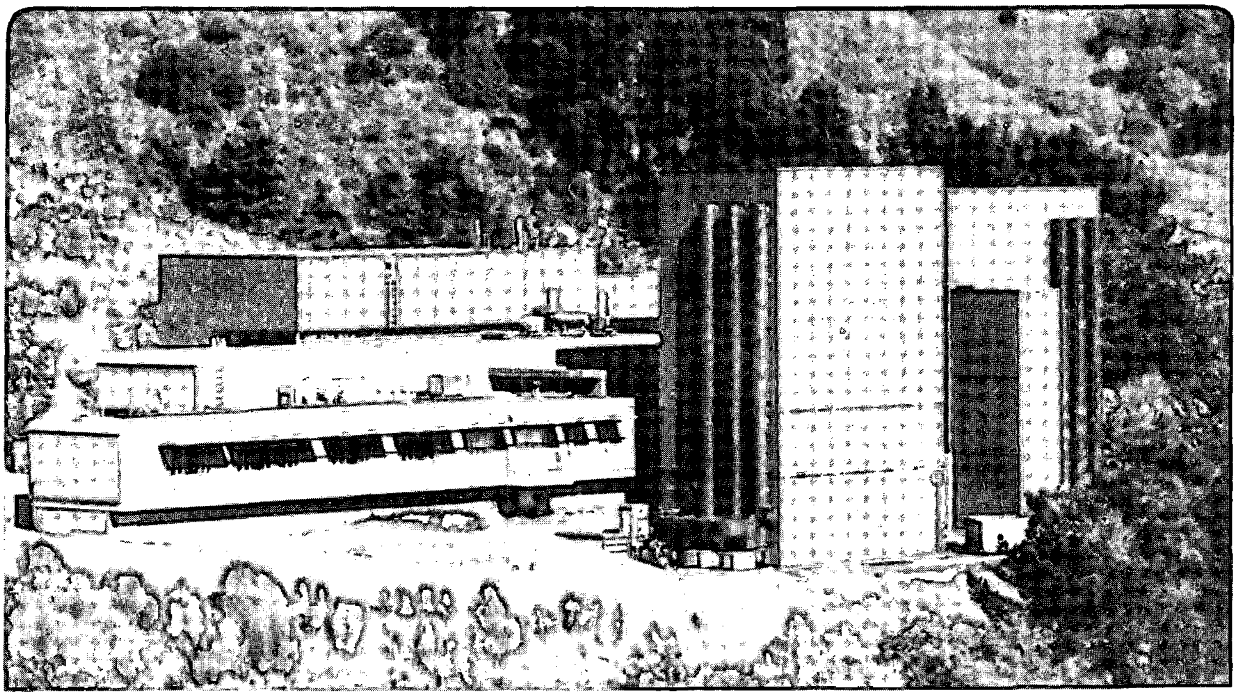

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Defect Control During Solid Phase Epitaxial Growth of SiGe Alloy Layers

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Abstract

A systematic study of the processing procedures required for minimizing structural defects generated during the solid phase epitaxial (SPE) growth of SiGe alloy layers is described. It includes high dose Ge implantation into Si at liquid nitrogen temperature (LNT), sequential carbon implantation, and an 800°C anneal. The LNT implantation step considerably reduces the density of end-of-range (EOR) defects relative to that found in SPE grown SiGe layers implanted at room temperature, while the sequential implantation of carbon ions before annealing effectively suppresses the formation of stacking faults that are found to form at a threshold peak concentration of about 6 at% Ge in the absence of carbon.

High dose Ge ion implantation and solid phase epitaxial (SPE) growth of SiGe alloy layers on (100) Si substrates have been studied by many investigators as synthesis routes for electronic devices requiring higher current gain than pure Si (e.g. heterojunction bipolar transistors (HBT)) made possible by the lower energy band gap in SiGe alloys[1-4]. Other investigators have used Ge-preamorphized Si surfaces to retard the diffusion of boron in devices requiring stable shallow junctions[5,6]. In every case however, annealing of these SiGe alloy layers induces the formation of dense concentrations of end-of-range (EOR) defects. Annealing of buried alloy layers also results in the generation of stacking faults within those regions of the alloy layer having the highest (peak) Ge concentrations. Such defects cause serious degradation of the electrical properties in functioning devices. Although considerable effort has been devoted to the suppression of these defects[1,2], no sustained attention has been given to the elimination of both classes of defects in one unit process. In the present work, we investigate synthesis and processing methods for the elimination of these defects by lowering the Ge implantation temperature and introducing sequential implantation of carbon for strain accommodation.

High dose Ge^{74} ions (Ge^+) were implanted into [100]-oriented Si to generate amorphous SiGe alloy layers with three different Ge peak concentrations (12 at%, 7 at% and 5 at%). The corresponding doses were 5×10^{16} cm^{-2}, 3×10^{16} cm^{-2} and 2×10^{16} cm^{-2} respectively. A Ge ion beam energy of 120keV was chosen and two implantation temperatures of 298K (RT) and 77K (LNT) were used. The 12at% Ge peak concentration alloy layer was then subjected to a second implantation of carbon ions (C^+) at room temperature (RT), using a C^+ beam energy of 20keV to position the implanted carbon ions at the same depth into the alloy layer as the 12 at% Ge peak. The nominal carbon dose was

2×10^{15} cm^{-2} to yield an anticipated 0.5 at% C peak concentration. The as-implanted Ge profiles were nearly Gaussian with an R_p of 65nm as measured from the Rutherford Back Scattering Spectrometry (RBS) data shown in Fig. 1, and the depth of the amorphous zone was 170nm for the LNT implanted alloy. SPE regrowth was performed at 800°C for 1 hour in a nitrogen ambient, after which there was no significant Ge redistribution according to the RBS data.

To characterize the structure and crystallinity of the regrown SiGe alloy layers, cross-sectional transmission electron microscopy (XTEM) was performed using both symmetrical and two-beam (diffraction vector g = 022) conditions in a <110> zone axis orientation. The XTEM micrographs in Fig. 2 show the results of high dose Ge ion implantation at room temperature. At 5 at% Ge peak concentration the SPE-grown SiGe alloy layer shows no stacking faults, but faults are clearly seen in the 12 at% Ge peak material. Note that both micrographs show a high density of EOR defects.

Previous studies[3,9] have attributed the formation of stacking faults in the peak concentration regions of the implanted alloy layer to the high strain conditions brought about by the localized concentration of the implantation species, and EOR defects have been shown[7,8] to be extrinsic dislocation loops formed by excess recoiled Si interstitials. When implantation is performed at room temperature, the available thermal energy is sufficient to cause dynamic annealing of amorphous SiGe layers as reported previously[10]. The dynamically-annealed, as-implanted SiGe shows a high density of very small EOR loops which subsequently grow in size during SPE processing.

The micrographs in Fig. 3 exhibit the results of LNT-implantation, after which the density of EOR defects is considerably reduced, as noted by others in earlier studies[2,7,8]. However, the density of stacking faults is not significantly reduced even though the peak concentration of Ge is down from 12 at% to 7 at% in this sample. Because there were no stacking faults in the sample with a 5 at% Ge peak, it is concluded that the threshold peak concentration of Ge for stacking fault formation is around 6 at%.

The attempt made in this study to restrict the formation of stacking faults in the LNT-implanted materials by sequential implantation of carbon proved successful. The small atomic radius of C (0.077 nm) compared to Ge (0.1224 nm), suggests that a controlled dose of C atoms can compensate the lattice strain induced by a high dose of Ge atoms during SPE regrowth of the SiGeC layer as long as both Ge and C atoms occupy substitutional sites in the Si lattice. In this study, implantation conditions were chosen to deposit a peak concentration of 0.5 at% C at the same depth as the amorphous SiGe alloy layer, 65nm, in the sample with 12 at% peak Ge. The XTEM micrograph in Fig. 4 shows the result of this process followed by SPE regrowth. It is clear that the overall density of all defects, including both stacking faults and EOR loops, is dramatically reduced. Fortunately because the diffusivities of C and Ge in the crystalline Si are so small at the 800°C annealing temperature, the Gaussian concentration profiles of both species remain relatively sharp, (Fig.1) in agreement with previous findings[4,11].

In summary, a sequential implantation process (Ge, LNT followed by C, RT) has been found to be an extremely effective method for reducing the defect concentration in SiGe alloy layers produced by Ion Beam Synthesis (IBS).

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Figure Captions

Fig. 1 As-implanted Ge profile following a high dose of Ge ions, 3×10^{16} cm^{-2} in a 170 nm thick amorphous SiGe layer, measured by RBS.

Fig. 2 XTEM micrographs of SPE-annealed SiGe alloy layers at 800°C for 1 hr after RTimplantation. The dark line indicates the sample surface.

a) Ge dose = 2×10^{16} cm^{-2} (5 at% Ge peak)

b) Ge dose = 5×10^{16} cm^{-2} (12 at% Ge peak)

Fig. 3 XTEM micrographs of LNT-implanted SiGe layers after SPE annealing at 800°C for 1 hr. The dark line indicates the sample surface.

a) Ge dose, 2×10^{16} cm^{-2} (5 at% Ge peak)

b) Ge dose, 3×10^{16} cm^{-2} (7 at% Ge peak)

c) Ge dose, 5×10^{16} cm^{-2} (12 at% Ge peak)

Fig. 4 XTEM micrograph of SiGeC layer regrown after Ge LNT-implant and C sequential implant (120 keV Ge, 5×10^{16} cm^{-2} + 20 keV C, 2×10^{15} cm^{-2}).

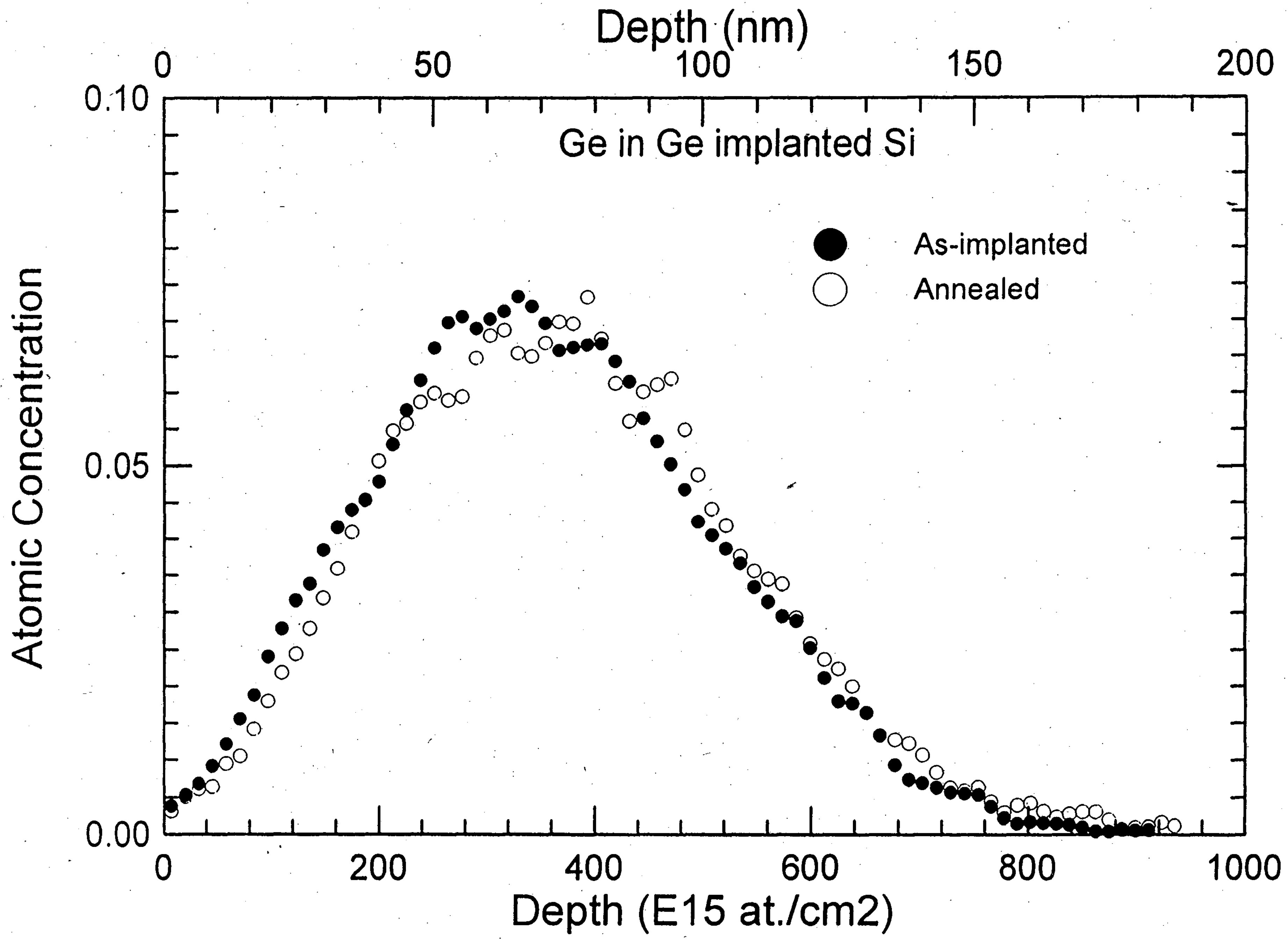
Depth (nm)
0
50
100
150
200
0.10
0.05
0.00
Ge in Ge implanted Si
● As-implanted
○ Annealed
Atomic Concentration
0
200
400
600
800
1000
Depth (E15 at./cm2)

Figure 1

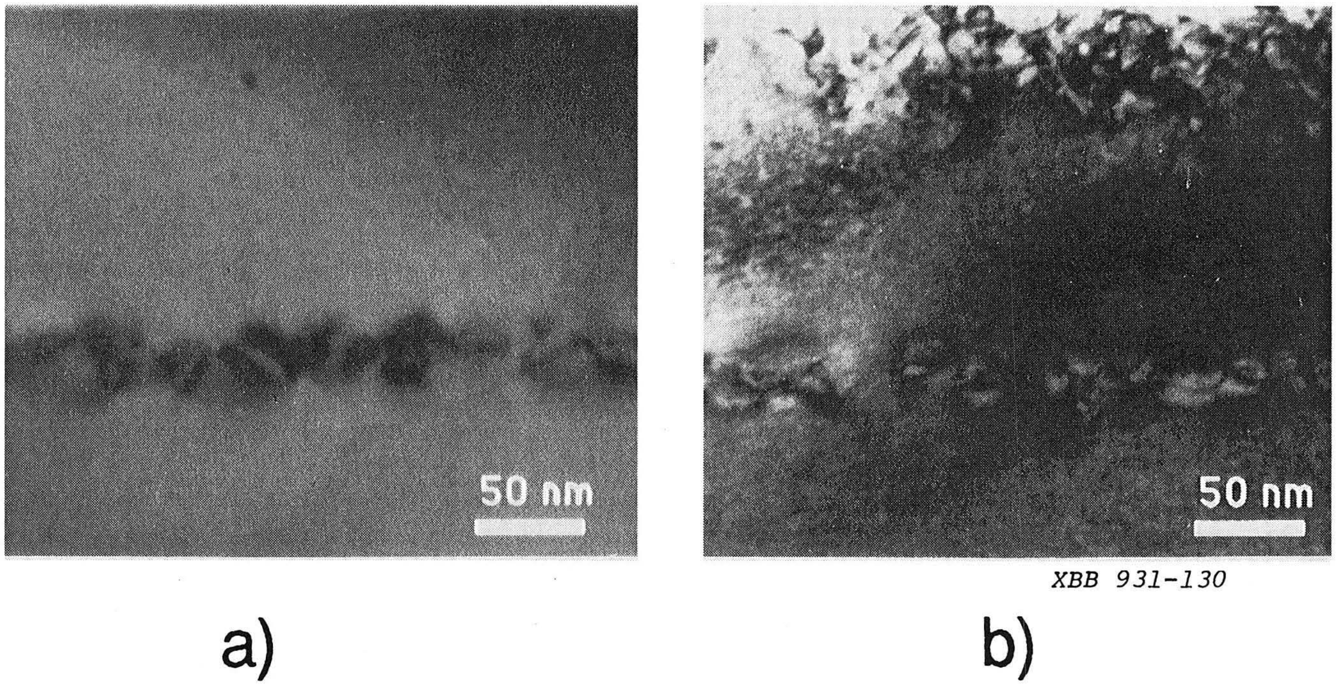

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Figure 2

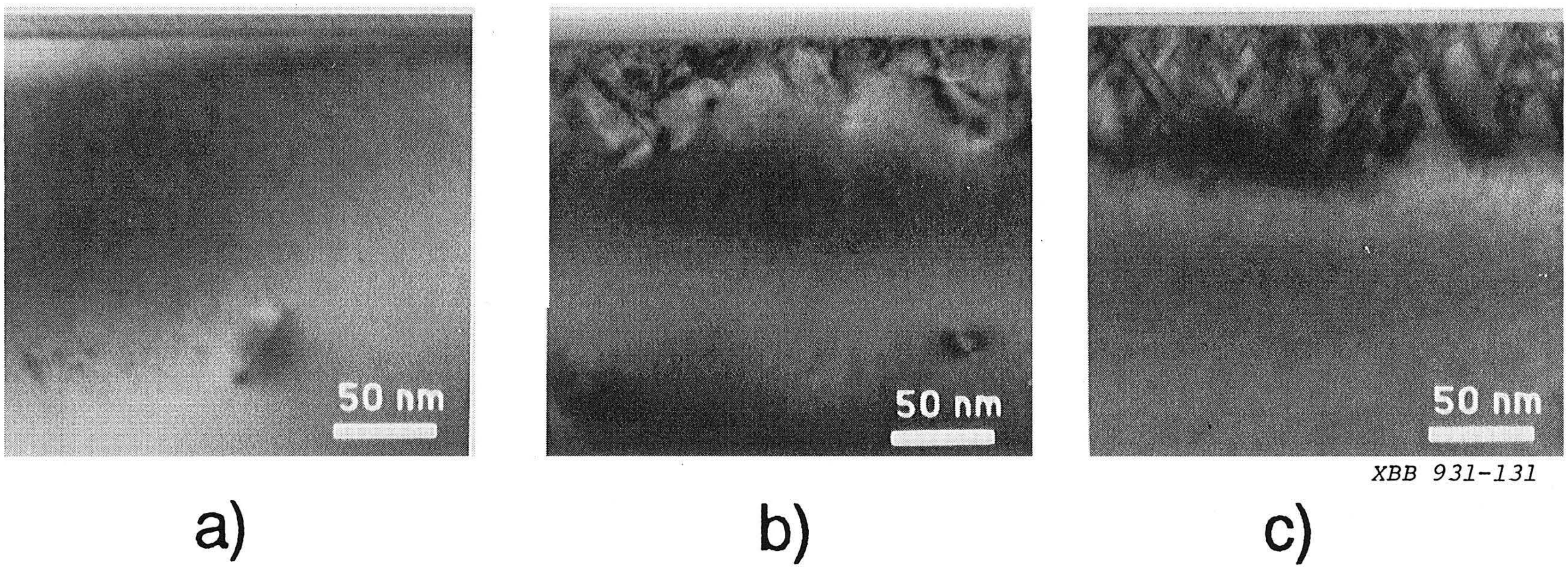

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Figure 3

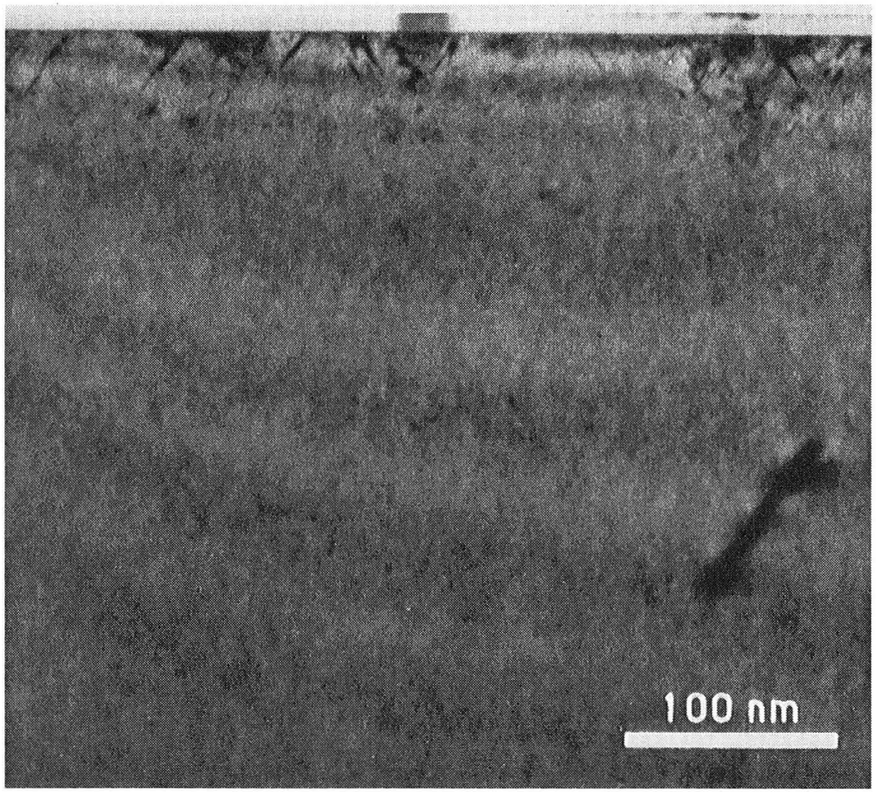

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Figure 4

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