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Electron-Beam Exposure Epitaxy (EBE-Epitaxy) for the Formation of SOI-GaAs Films on CaF_2/Si(111) Structures

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A novel heteroepitaxy technique, which we call as an electron-beam exposure epitaxy (EBE epitaxy), has been employed in growing GaAs films on CaF_2/Si(111) structures. In this method, prior to the growth of GaAs films, the surfaces of CaF_2 are exposed to an electron-beam under impingement of arsenic fluxes. Consequently, thin GaAs films with excellent crystallinity and smooth surfaces could be obtained on the CaF_2/Si(111) structures. The electron beam exposure effect strongly depended upon the electron dose. It has been also found that the GaAs films grown by this method have preferentially and dominantly type A orientation which is identical to that of the CaF_2. Cross-sectional transmission electron microscopy has shown that the defect density in the GaAs films is remarkably reduced by employing the EBE epitaxy.

1. Introduction

GaAs on insulator structure is one promising candidate of ideal structures for fabrication of high speed LSI's, optoelectronic IC's and 3-dimensional IC's for the future. Moreover, if GaAs-SOI (semiconductor-on-insulator) structure is formed on Si substrates, it will bring further advantages such as the reliability and the high thermal conductivity of Si. In order to realize this GaAs-SOI structure, we have used alkaline earth fluoride of CaF_2 as an insulating material, and shown the feasibility of this structure.[1-2] However, it was difficult to obtain a thin GaAs film having good quality because the growth of GaAs on CaF_2 was initiated three-dimensionally and the crystalline quality of the film degraded near the interface between GaAs and CaF_2. So, it was cosidered to be insufficient to make the best use of the merit of SOI structure, that is, high speed characteristic due to reducing the loading capacitance and suppressing the short channel effect.

In this presentation, a novel heteroepitaxy technique, which we call as an electron-beam exposure epitaxy (EBE epitaxy) technique, is proposed to solve the above problems.

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2. Experimental Procedure

Growth of GaAs/CaF_2/Si(111) structures was carried out in the three-chamber MBE system, consisting of a loading chamber, a fluoride growth chamber and a GaAs growth chamber. Details of the CaF_2 growth process were described in ref. 3. In brief, single-crystal CaF_2 films with thicknesses of 150 to 250nm were grown on (111) oriented Si substrates at 700°C. Then, the CaF_2/Si(111) structures were tranferred to the GaAs growth chamber and the sample surfaces were exposed to electrons under impingement of As fluxes. The electron beam (e-beam) was generated by an RMEED (reflection medium energy electron diffraction) gun with a maximum energy of 3kV and it was electrostatically scanned along one direction in order to improve the uniformity of the exposure. The incident angle of the beam to the sample surface was about 3°. Finally, 320nm thick GaAs films were grown on the CaF_2/Si structures at a temperature of 550°C. A typical growth rate of the films was

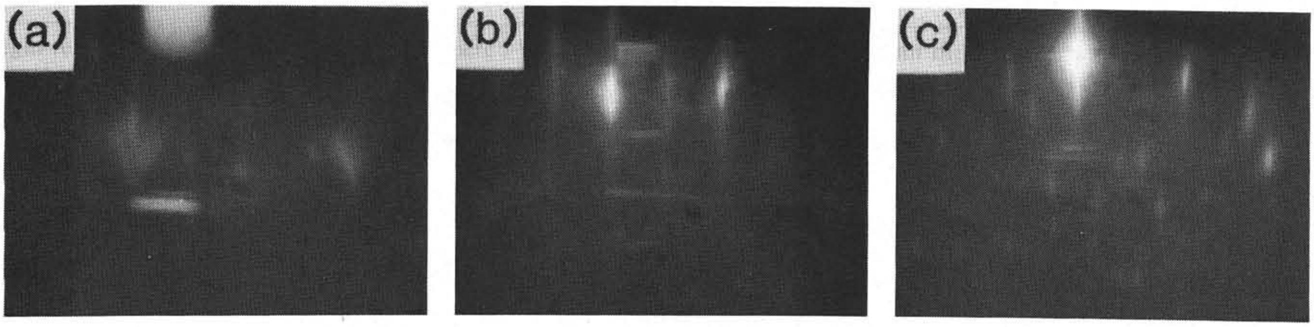

Fig. 1 Diffraction patterns of the surfaces of 320nm thick GaAs films grown, (a) on the unexposed CaF_2/Si(111) structure, (b) and (c) on the electron-beam exposed CaF_2/Si(111) structure. The As-stabilized (2×2) surface structure (b) is transitted to the Ga-stabilized (√19×√19) surface structure (c) at 550°C without As flux impinging. The exposure was done under impingement of As fluxes with a electron dose of 540μC/cm^2. 3keV, <110> azimuth.

1μm/hr and the flux ratio of As_4 to Ga was kept around 60.

3. Results and Discussion

Figure 1(a) shows an RMEED diffraction pattern taken from a 320nm-thick GaAs film grown on unexposed CaF_2/Si(111) structure. The pattern is spotty and a number of off-angle streaks are observable, which indicates that the surface is rough and many facet planes exist on the surface. This is probably due to three dimensional nucleation of the growth of GaAs on CaF_2. On the other hand, as shown in Fig. 1(b), a GaAs film grown on e-beam exposed CaF_2/Si(111) structure under impingement of As fluxes gives a sharp streaky pattern, indicating a smooth surface. In addition, we can see the As-stabilized (2×2) surface structure in the pattern of Fig. 1(b). This pattern was taken under As flux impingement. On the contrary, when the As beam was cut off at 550°C, the diffraction pattern changed to the Ga-stabilized (√19×√19) structure,[4] as shown in Fig. 1(c). From this transition of surface structure, it can be said that the uppermost layer of GaAs films grown on e-beam exposed CaF_2/Si(111) structures is (111) As face.

The crystalline quality of the GaAs films grown by the EBE-epitaxy was investigated as a function of an electron dose using Rutherford backscattering spectroscopy (RBS) with 1.5MeV $^4He^+$ ions. It is found from Fig. 2 that the crystallinity of the films strongly depends on the dose and it is improved with increase of the electron dose up to a dose of 540μC/cm^2. The best channeling minimum yield χ_{min} near the surface of the film is 4.6% which is close to the value obtained from a bulk GaAs crystal (≃3.5%). At the higher dose, however, the crystallinity of the films again deteriorates.

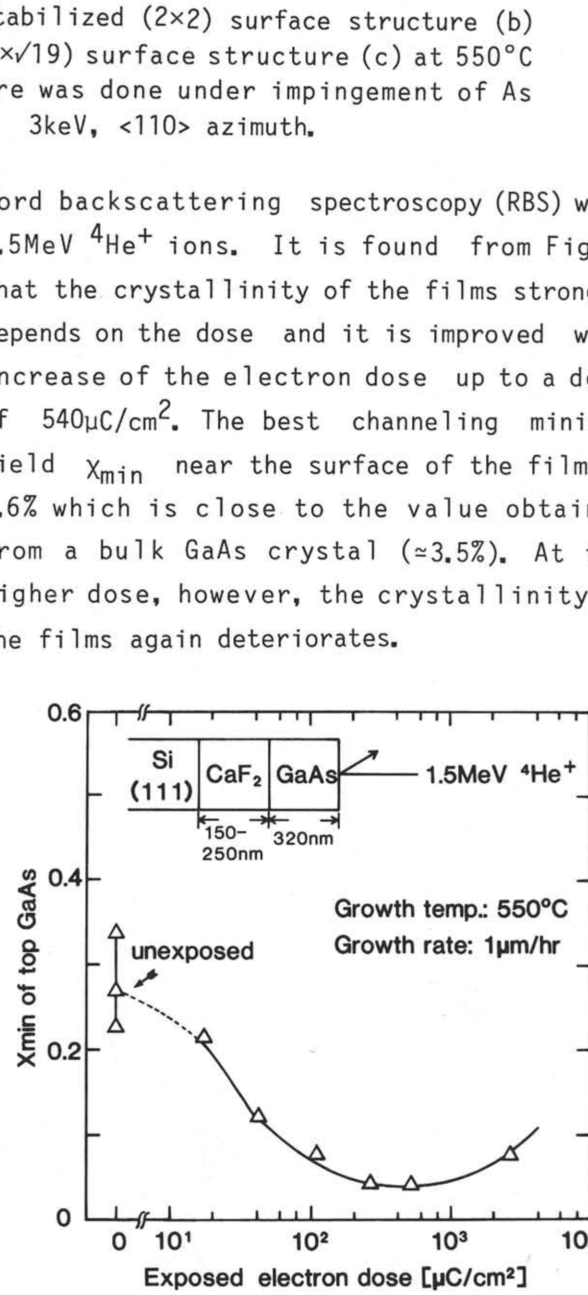

Fig. 2 Electron dose dependence of the channeling minimum yield χ_{min} near the surface of GaAs films grown on the e-beam exposed CaF_2/Si(111) structures under impingement of As fluxes. The film thicknesses were about 320nm.

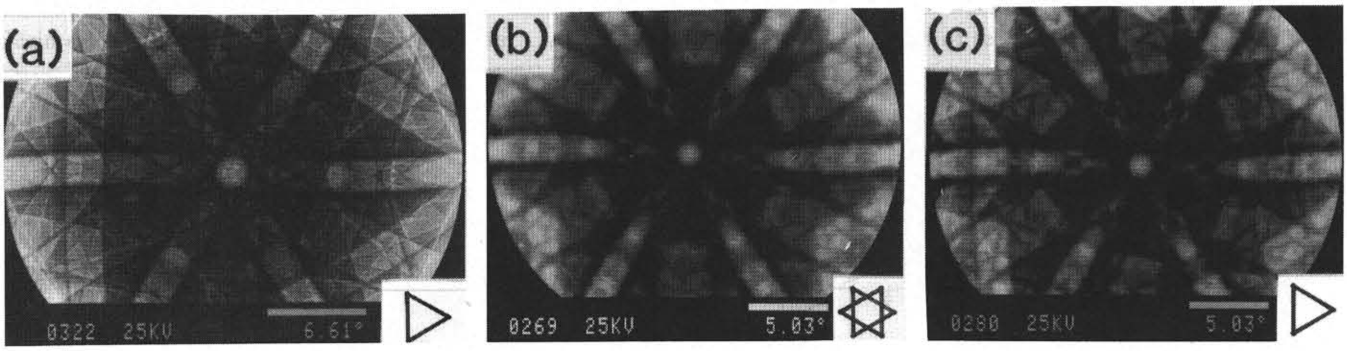

Fig. 3 Typical electron channeling patterns for (a) a CaF_2 film grown on the (111) oriented Si substrate, (b) a GaAs film grown on the unexposed CaF_2/Si(111) structure, and (c) a GaAs film grown on the e-beam exposed CaF_2/Si(111). The e-beam exposure conditions are the same as those in Fig. 1(b) and (c).

The crystallographic orientation of the GaAs films was examined by the electron channeling pattern method using SEM[5]. The in-plane orientation can be determined from the triangles formed by {311} bands, as indicated in the insets of Fig. 3. It is found from the pattern shown in Fig. 3(a) that the intermediate CaF_2 film has the 180° azimuthal rotation on the Si substrate, namely type B orientation, as it can be expected from our previous RBS measurement[6]. The orientations of the top GaAs films grown on the unexposed CaF_2/Si(111) structures were found to be either type A dominant (the same orientation with the underlying CaF_2 film) or mixture of both type A and B crystallites. A typical channeling pattern for a GaAs film with the mixed crystallites is shown in Fig. 3(b). On the contrary, the orientation of the GaAs films grown on the CaF_2 exposed to an e-beam at moderate doses was found to be always type A dominant. Figure 3(c) shows the channeling pattern for a sample, in which the CaF_2 surface was exposed to electrons to a dose of 540μC/cm^2 (3.4×10^{15} electrons/cm^2) under impingement of As fluxes. We can see from the channeling pattern that no mixing of both crystallites occurs at this electron dose. However, mixing of both crystallites and degradation of the surface morphology were again observed at such a high dose as 2.6mC/cm^2 (1.6×10^{16} electrons/cm^2).

In order to investigate the surface morphology and to determine the structural defects in the GaAs films, cross-sectional transmission electron microscopy (X-TEM) observation was carried out. A GaAs film grown on the unexposed CaF_2/Si(111) structure shown in Fig. 4(a), exhibits a very rough surface having a number of facets, as expected from the RMEED pattern in Fig. 1(a). Further, we find a number of linear defects (dislocations) in the GaAs film. On the contrary, as shown in Fig. 4(b), the GaAs film grown on the e-beam exposed CaF_2/Si(111) structure shows very flat surface. The defect density is remarkably reduced near the surface region about 100nm away from the interface between GaAs and CaF_2. It is noteworthy that a few planar defects (microtwins) appear in the film grown on the e-beam exposed CaF_2/Si(111) structure which are absent in the unexposed case. The reason for the appearance of the planar defects is not clear at present. However, it is considered from observations of similar defects in GaAs/CaF_2/Si(100) structure[1] and Si/CaF_2/Si structure[7] that the planar defects are generated by the compressive stress due to the difference in the thermal expansion coefficient between GaAs and CaF_2. Actually, we have preliminarily observed the strengthened adhesion of the GaAs film to the CaF_2 film by

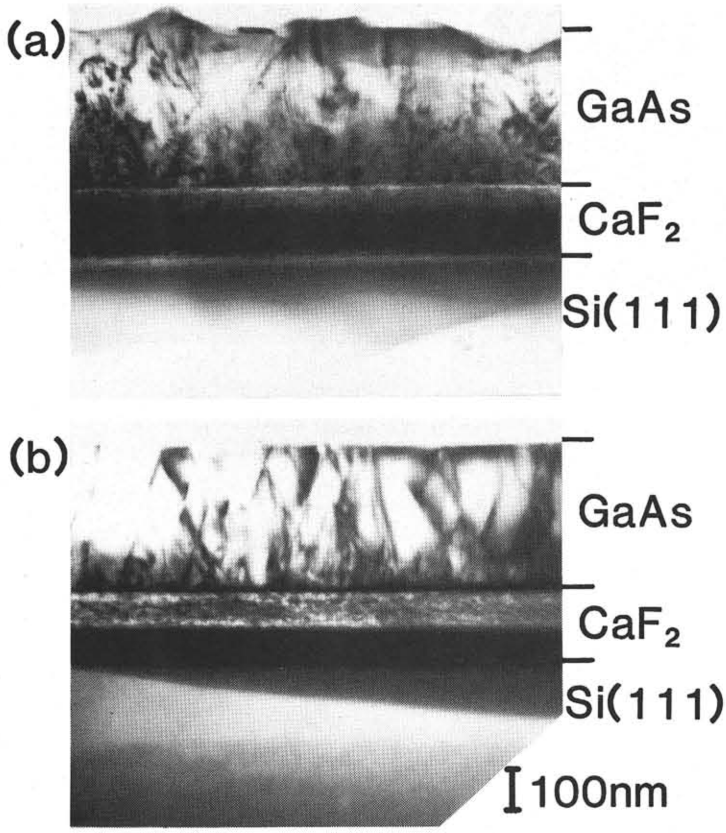

Fig. 4 Brightfield cross-sectional TEM micrographs of $GaAs/CaF_2/Si(111)$ structures, in which (a) is the unexposed case and (b) is the e-beam exposed case. The samples of (a) and (b) are identical to those shown in Fig. 3(b) and (c), respectively.

e-beam exposure.

One more interesting feature in Fig. 4(b) is the appearance of a boundary in the e-beam exposed CaF_2 film. The boundary is not observable in the unexposed CaF_2 film shown in Fig. 4(a). The depth of the boundary from the upper interface is about 80nm in this sample (exposed to a dose of 540μC/cm^2 with a electron energy of 3kV at a incident angle of about 3°). The depth of the boundary was found to increase with the exposed electron dose. From these observations, it can be considered that the boundary appears due to alteration of CaF_2 properties by the e-beam exposure. This fact may account for the experimental result reported by Fathauer and Schowalter[8] that electric characteristics of CaF_2/Si structure degraded after e-beam exposure.

4. Conclusion

We succeeded in growing single-crystal GaAs films with both excellent crystalline quality and smooth surfaces by employing the novel EBE epitaxy (electron-beam exposure epitaxy) technique. It is speculated that the improvement of the quality of the SOI-GaAs films is caused by the improvement of the wettability between GaAs and CaF_2, due to the dissociation of uppermost fluorine atoms of CaF_2 by e-beam exposure.[9] From this speculation and the appearance of the varied CaF_2 layer formed by an e-beam exposure, as known in the observation of X-TEM, it may be desirable to reduce the electron energy for an ideal EBE epitaxy. The similiar effect as an EBE epitaxy in heteroepitaxy of semiconductor on fluorides may be also expected by other methods such as photons[10] which can controllably dissociate the fluorine atoms from the CaF_2 surface.

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