Title

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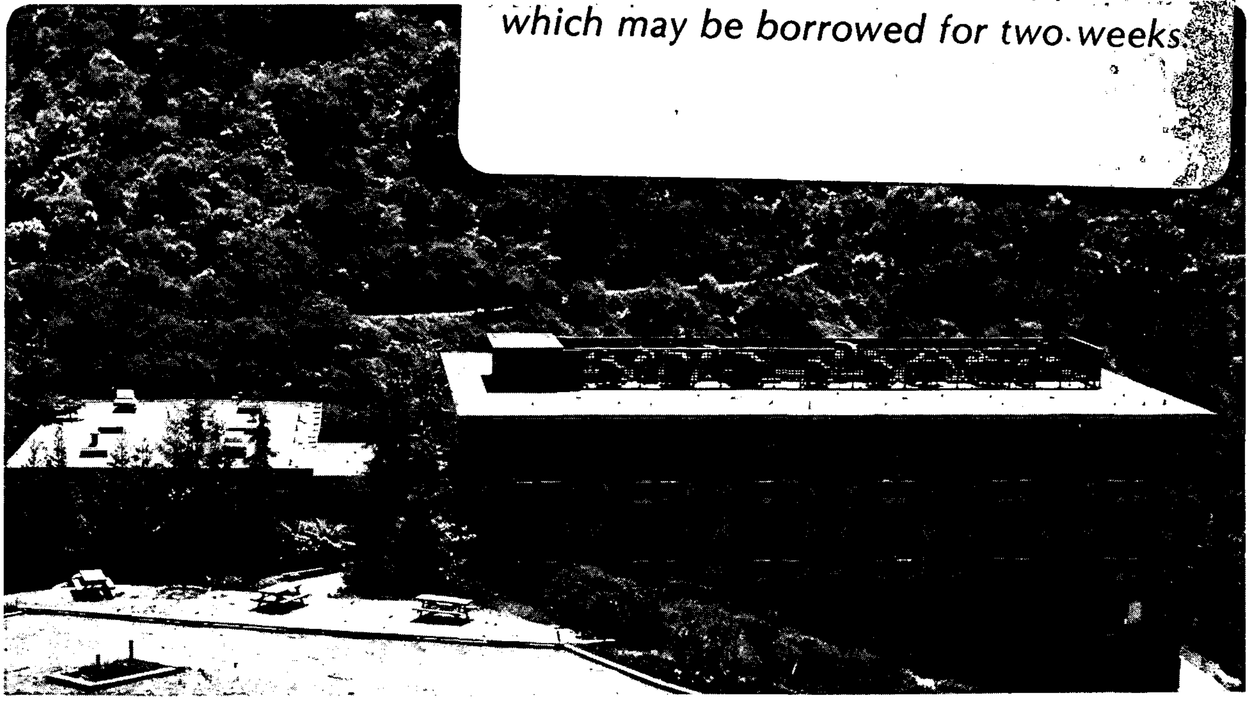

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RAMAN SCATTERING SPECTRUM ALONG A BEVEL ETCHED GaAs ON Si, TEM STUDY AND GaAs P-I-N PHOTODETECTOR ON Si

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Abstract

Raman scattering is measured along a bevel etched GaAs epitaxial film grown on Si by molecular beam epitaxial (MBE). From the correlation length profile of Raman scattering, most dislocation lines are confined in the 2000Å regions close to the interface. The strain profile calculated from the Raman peak shift shows that about 0.6% compressive strain exists near the interface because of lattice mismatch. However, as one moves away from the interface, the compressive strain is gradually counterbalanced by thermal expansion. Transmission electron microscope (TEM) studies of the local dislocation image and properties show that an ultra clean Si surface is essential for dislocation confinement. From high resolution TEM, we find that the distance between dislocations at the interface is nonuniform, varying from 50Å to 125Å with an average distance at 81Å. Finally, a GaAs p-i-n photodetector on Si substrate is fabricated. Even though a normal photoresponse curve is obtained, the high dark current (50nA) and relatively low responsivity (0.01A/W) show that the material quality needs to be further improved to make a minority carrier vertical transition device.

Introduction

Lately the research on epitaxial growth of GaAs on Si substrate is developing quickly because it not only invokes a number of interesting scientific challenges but also provides practical benefits in applications such as GaAs VLSI digital circuit and opto-electronic integration.[1–5] However, several fundamental problems exist in the epitaxial growth of GaAs on Si. First, the growth of a polar crystal on a non-polar crystal tends to form anti-phase domains (APD) which induce static charge sheets in the GaAs thin film. Second, the relatively large lattice mismatch (≈4%) between GaAs and Si will induce many dislocations near the interface and some of them may propagate towards the crystal surface. Third, the large difference in thermal expansion coefficients between GaAs and Si causes a very high stress which often makes the sample crack during wet etch processing.

To investigate the strain and dislocation properties as mentioned above, we perform a Raman scattering experiment which can measure the strain and dislocation density profile from the GaAs and Si interface to the GaAs surface. On the other hand, cross section TEM and high resolution TEM provide us with information about dislocation image and properties. A GaAs on Si p-i-n photodetector is also fabricated for the first time and the results are compared with a normal GaAs p-i-n photodetector.

Raman Scattering

GaAs is grown on a Si substrate oriented 4 degrees off the [100] direction towards the [110] axis by MBE. As shown in the insert of Fig-1, a bevel of 0.1 degree has been etched in the GaAs epitaxial film, so that the Raman spectrum of GaAs layers can be measured as a function of distance from the GaAs/Si interface. The 5145Å line from an Ar$^+$ laser is used to trigger the Raman signal. The Raman experiment is performed at room temperature in the $x(yz)\bar{x}$ back-scattering geometry, where x,y,z refer to the [100], [010] and [001] crystallographic axes respectively. In this scattering geometry, the longitudinal optical (LO) phonon of GaAs is allowed by the selection rules, while the transverse optical (TO) phonon is forbidden. The LO phonon Raman scattering intensity variation with distance from the interface is shown in Fig-1. We can determine the transmission coefficient of the GaAs film form the variation of the Si phonon intensity provided that this absorption coefficient is not varying with the GaAs film thickness. The solid curve in Fig-1 shows a fit to the experimental points with a constant GaAs penetration depth of 1580±20Å.

The normalized Raman spectrum at different depths from the interface is shown in Fig-2. The GaAs LO phonon peaks become broader and more asymmetric when the layers are closer to the interface. This phenomenon can be explained as follows.

In a perfect crystal, only zone center ($q=0$) phonon modes are excited for one-phonon Raman scattering because of quasi-momentum conservation. For a disordered lattice, however, phonons can be localized to a region of space L, and as a result quasi-momentum conservation will be relaxed so that off-center phonons ($q\neq0$) can be excited.$^{6-8}$ The participation of off-center phonon scattering causes the asymmetric non-Lorentzian lineshape near the interface. On the other hand, the phonon linewidth near the interface is broader than the phonon linewidth for layers farther than half micron from the interface because the phonon lifetime is reduced by disordered material. Both the LO phonon lineshape and linewidth, therefore, contain information about the crystal quality. We adopt the spatial correlation model developed by Richter^6 and Tiong et al.,^{8} to calculate the spatial correlation length L from either the phonon width or the lineshape asymmetry. Fig-3 shows the correlation lengths of the GaAs film as a function of distance from the interface. Those calculated correlation lengths are related to the average distance between two dislocation lines. The abrupt increase of correlation length around 2000Å from the interface shows that most dislocations can not propagate further.

In addition, the strain profile can also be calculated from the Raman peak frequency shift if a uniform and isotropic two-dimensional strain is assumed.^{7} As shown in Fig-3, a compressive strain is present in the GaAs layers near the interface is present. This may be due to the lattice mismatch between GaAs and Si. This compressive strain from lattice mismatch is counterbalanced by the tensile strain from thermal expansion, so the GaAs surface becomes almost strain free for a 2.3μm film.

For the region thicker than 5000Å, the dislocation density is too low to be detected by Raman scattering techniques. The discrete feature and local image of dislocation lines will be studied by TEM.

TEM Study

Figs-4 and 5 show the TEM cross sections of two GaAs on Si samples grown by MBE. Fig-4 shows the growth of GaAs on an oxygen and carbon contaminated Si surface. Very characteristic triangular protrusions are observed near the Si surface giving rise to a high dislocation density. Many dislocations and stacking faults generated at the interface propagate to the surface layer of GaAs. The density of dislocations estimated in the near surface area is in the range of 5 to $9\times10^{9}\mathrm{cm}^{-2}$. If the Si surface is clean (Fig-5), triangular features are not formed at the interface and the density of stacking faults formed at the interface is lower as well. Many of the misfit dislocations are tangled and confined in the near Si/GaAs area within 0.3μm from the Si substrate. This film quality is quite acceptable even without any strain layer superlattice or thermal annealing. This observation indicates that an ultra clean Si substrate is necessary for high quality GaAs on Si growth.

As was found before,[5] two types of dislocations are formed at the interface. Most of the dislocations (≈85%) have their Burgers vector parallel to the interface (Fig-6) and only about 15% have their Burgers vector inclined to the interface. This small fraction of dislocations with inclined Burgers vector is probably the reason for the much lower density of dislocations ($\approx5\times10^{7}\mathrm{cm}^{-2}$) in the near surface area of the GaAs. The average distance between the dislocations at the interface is one dislocation per 81Å. However, the distribution of the dislocations at the interface in not uniform. There are areas where the distance between the dislocations (estimated from high resolution TEM pictures) is only 50Å apart but there are other areas where dislocations are separated as much as 125Å. Higher stress (≈2.5%) is built up in the areas where dislocations are closer to each other. Stress is almost completely released (≈0.1%) in the areas where dislocations are far from each other. One would expect that dislocations which are close together interact differently from dislocations which are further apart. This nonuniformity will influence the final dislocation distribution in the top surface layer of GaAs, where one can find both areas which are dislocation free and areas which have higher dislocation densities.

P-I-N Photodetector

In terms of device characteristics, most majority carrier devices like FETs have been reported by several groups[1,2] showing comparable performance with those devices made on a GaAs substrate. LEDs and lasers have also been recently reported even though reliability and lifetimes are much worse than those on a GaAs substrate.[9,10] Photodetectors, however, are almost not reported yet besides the lateral conductive photoconductors which is most insensitive to dislocations and other defects. We fabricated a p-i-n homojunction GaAs photodiode having the device structure shown in Fig-7. The commonly used two-step growth were adopted and three InGaAs/GaAs strain layer superlattices, ten 50Å/100Å periods each superlattice, are grown as dislocation filtering layers. The high dark current (50nA at -0.2volt) restricts this device from working at higher bias. The normalized photoresponse with respect to wavelength is shown in Fig-8. The peak responsivity at room temperature occurs at 0.78μm (1.59ev) and cuts off at 0.88μm (1.41ev). The lack of abnormal peaks at longer wavelength (up to 1.5μm) means that there is no significant deep level absorption. High dark current can be explained by higher dislocation density (approximately 10^3 to 10^4 times) in the device active region than in the GaAs substrate. The responsivity without an anti-reflection coating is about 0.01A/W, which is also relatively low.

Conclusion

In summary, we use Raman scattering to scan across a beveled edge of GaAs on Si to find out the strain as well as the average dislocation density profiles. Compressive strain is present at the interface because of the GaAs and Si lattice mismatch but this strain is gradually counterbalanced by the tension from thermal expansion. The dislocation image and its propagation are studied by TEM, which indicates that an extremely clean Si surface is essential. The distance between two dislocations near the interface is nonuniform. Finally, the first GaAs on Si p-i-n photodetector is demonstrated. Despite its high dark current and relatively low responsivity, a normal photoresponse curve without any deep level peak is observed.

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Figures

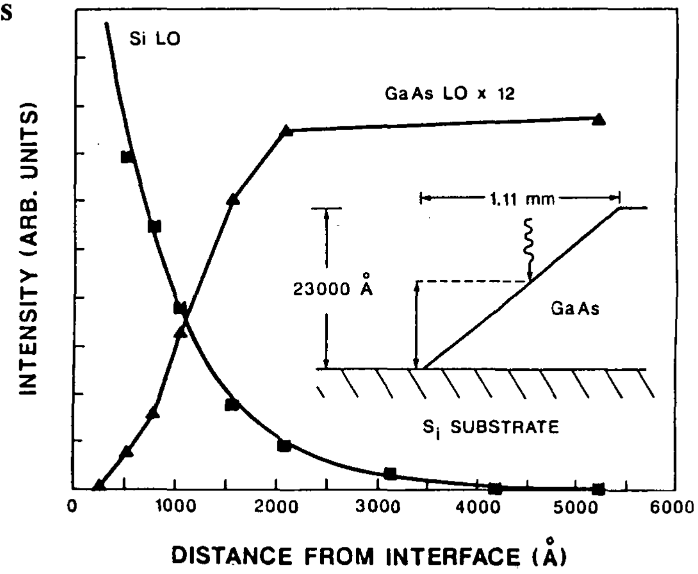

Figure 1. The LO phonon Raman scattering intensity profile. The epitaxial structure of the sample with bevel angle 0.1 degree is also shown.

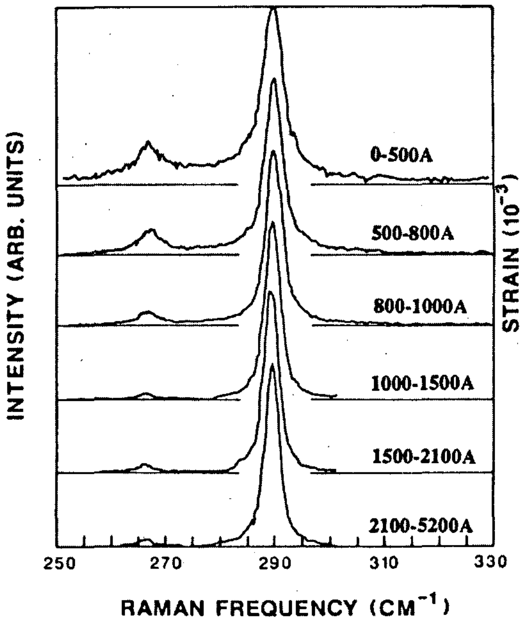

Figure 2. Normalized Raman scattering at different distances from the interface. Both LO phonon and TO phonon peaks can be identified.

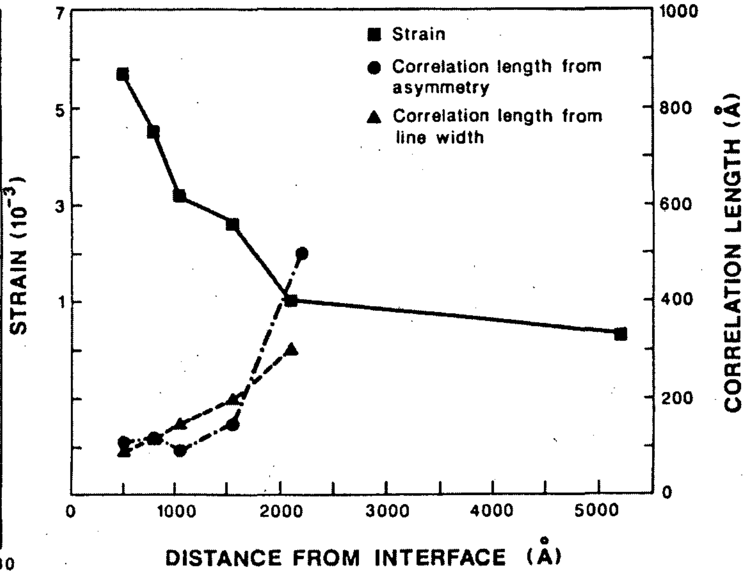

Figure 3. Calculated strain and correlation length profiles from Raman scattering. The correlation length obtained from either Raman linewidth or lineshape asymmetry corresponds to the average dislocation distance.

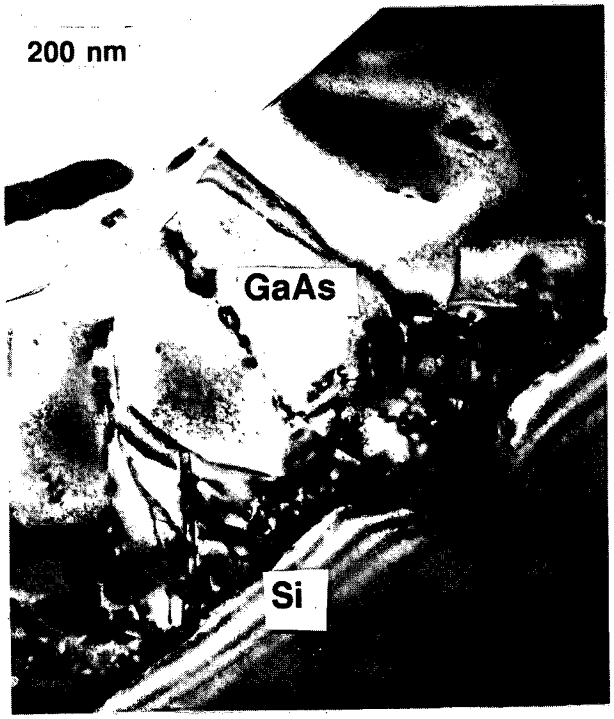

Figure 4. TEM picture of GaAs grown on an oxygen and carbon contaminated Si surface. A number of dislocations and stacking faults are observed and many of them propagate to the GaAs surface layer.
XBB 860-8798

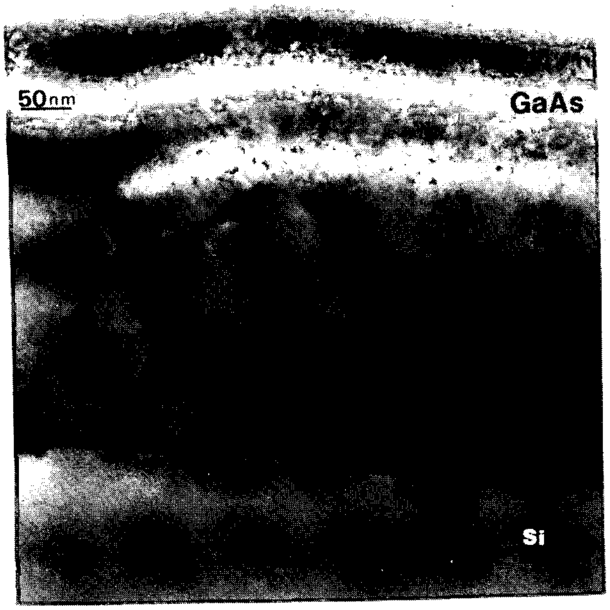

Figure 5. A TEM picture of GaAs grown on a clean Si surface. In contrast to Fig-4, most of the dislocations are confined near the interface or are bent in the middle so that the GaAs surface has very low dislocation density. XBB 874-3000

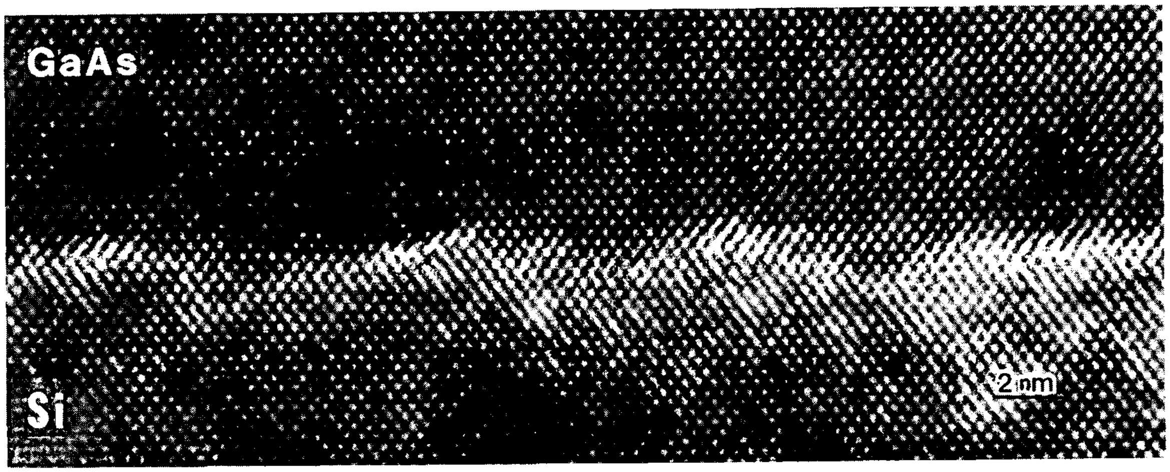

Figure 6. High resolution TEM picture of GaAs and Si interface. In this picture, We look at (110) plane where dislocations at the interface are found on the (100) plane with Burgers vector parallel to the interface. All of these dislocations in this picture are not inclined. XBB 874-3001

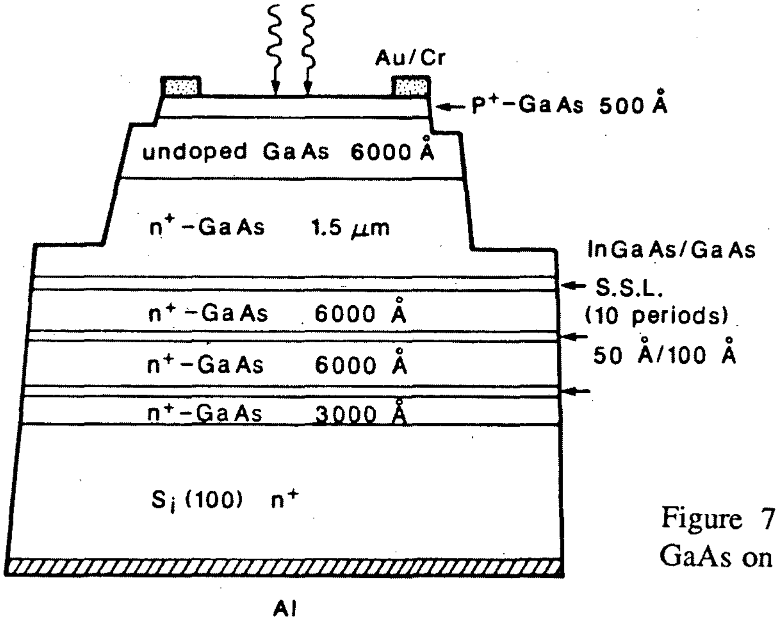

Figure 7. Schematic diagram of the GaAs on Si p-i-n photodetector.

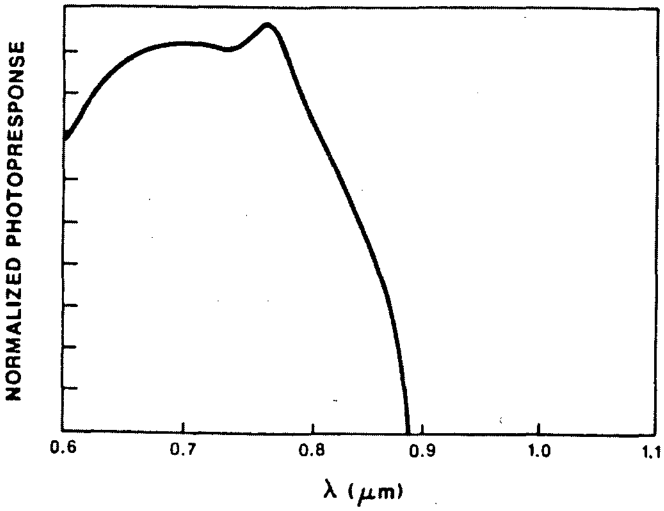

Figure 8. The normalized photoresponse curve of the GaAs on Si p-i-n diode.