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Growth of stress-released GaAs on GaAs/Si structure by metalorganic chemical vapor deposition

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A stress-released GaAs layer was grown on GaAs bonded to Si substrate with the combination of epitaxial lift-off technique and regrowth by metalorganic chemical vapor deposition. The GaAs thin film was bonded to Si substrate using SeS_2 and another GaAs layer was regrown. The photoluminescence peak wavelength and the slope of the time resolved photoluminescence decay of GaAs/Si are almost the same as those of GaAs grown on GaAs substrate. © *2000 American Institute of Physics.* [S0003-6951(00)01052-4]

The main problems for GaAs-on-Si technology are large lattice mismatch and the thermal expansion mismatch which produce the threading dislocation and the stress in the epitaxial layer. Especially the growth of stress-free GaAs on Si substrate is essential to reduce the dislocation density lower than $10^6\,cm^{-2}$ because the origin of the dislocation is the stress due to the difference of the thermal expansion coefficients between GaAs and Si.[1] Until now, much effort has been paid to grow low dislocation density GaAs on Si substrate by using thermal cycle annealing,[2] strained layer superlattice,[3] etc. However, the problem of thermal mismatch has not been solved yet. Although the stress-reduced GaAs on Si substrate has been reported by selective epitaxy,[4] under cut GaAs-on-Si,[5] etc., there remain problems for the device applications because of the area as small as the order of $10-100\,\mu m^2$.

Recently, we have obtained a high quality stress-free GaAs layer on Si substrate by transferring the GaAs thin film to the Si substrate using the wafer bonding technology. In this technique SeS_2 was used between GaAs and Si to form a strong bonding.[6] This letter proposes the regrowth of stress-released high quality GaAs layer on earlier mentioned GaAs/Si structure.

Epitaxial growth was performed by using conventional metalorganic chemical vapor deposition. The source gases for Ga, Al, and As are trimethylgallium, trimethyaluminum, and arsine, respectively. The growth temperature is 750 °C and V/III ratio is 40. The substrate is (100) oriented Si with the size of $5\,mm\times 5\,mm$. First, 3-μm-thick GaAs layer is grown on GaAs substrate with 10-nm-thick AlAs intermediate layer. Si substrate is treated in SeS_2 solution dissolved in CS_2. Two samples are sandwiched in the furnace at 350 °C under N_2 ambient for 10 min. At this stage the strong bonding can be achieved between GaAs and Si as reported previously.[6] The sample is immersed in HF:H_2O (1:2) for about 1 day at room temperature to undergo the epitaxial lift-off (ELO) process by the selective etching of AlAs to obtain a GaAs thin film on Si substrate. As reported in Ref. 6, the photoluminescence (PL) intensity and the PL peak wavelength of GaAs thin films on Si substrate are almost the same as those grown on GaAs substrate at this stage. Finally, another 3-μm-thick GaAs layer was regrown on this sample. The cross-sectional structure is schematically shown in Fig. 1. GaAs substrate was also used for the comparison. The samples were characterized by Nomarski optical microscope, PL at 77 K, time resolved PL at room temperature, and double crystal x-ray rocking curve using (400) diffraction. The Nomarski surface micrographs of GaAs on Si shows that the surface is very smooth without any waviness.

Figure 2 shows the 77 K PL spectra of GaAs/Si and GaAs/GaAs. Usually the PL peak wavelength of GaAs grown epitaxially on Si substrate is shifted toward longer wavelength side due to the tensile stress caused by the difference of the thermal expansion coefficients between GaAs and Si. It is explained that the GaAs grown on Si substrate at growth temperature is almost stress-free and the stress is increased during the cooling down process after the crystal growth.[7] But, the PL peak wavelength of the present GaAs/Si is almost the same as that grown on GaAs substrate. Although the PL peak wavelength of GaAs/Si grown by heteroepitaxy under the similar conditions is about 15 nm shifted towards the longer wavelength side,[8] the peak shift of the present GaAs/Si is as small as 1.5 nm. It means that the

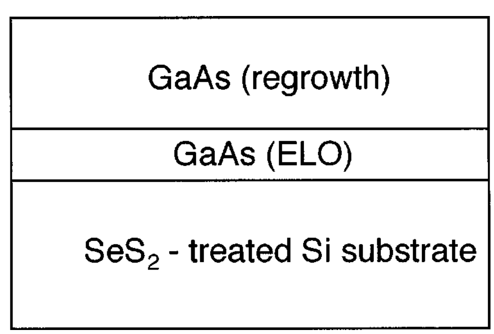

FIG. 1. Structure of GaAs on Si substrate using ELO and regrowth.

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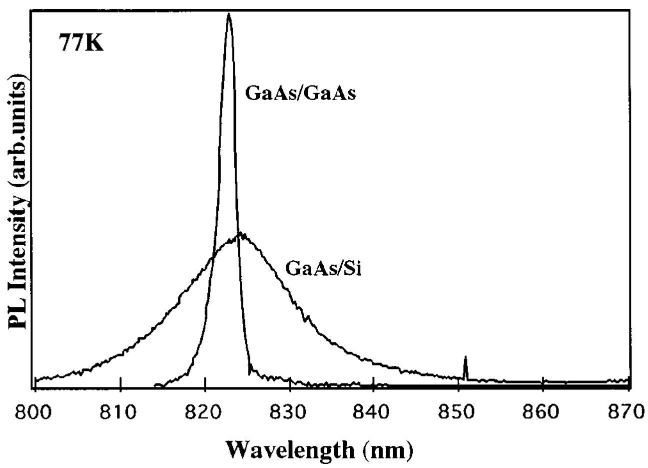

FIG. 2. 77 K PL spectra of GaAs grown on Si substrate by ELO and regrowth and GaAs grown on GaAs substrate.

stress of GaAs on Si substrate is almost relaxed by this method since the stress does not depend on the thickness in this range.[9] The PL intensity is a little degraded (about a half) compared with GaAs on GaAs substrate, but it is superior to heteroepitaxial GaAs-on-Si by the two step growth method. The broad full width at half maximum (FWHM) would be due to the incorporation of impurity from Si substrate or SeS_2. The secondary ion mass spectroscopy analysis is necessary to check the level of impurity incorporation for Se or Si during the regrowth process.

In order to evaluate the characteristics of minority carrier properties, the minority carrier lifetime was measured by time-resolved PL. Figure 3 shows the time-resolved PL decay of GaAs/Si and GaAs/GaAs. Because the sample is not a double heterostructure, the slope corresponding to the ''effective minority carrier lifetime'' is a little shorter than the real ''bulk lifetime,'' which is affected by the surface recombination velocity.[10] The effective minority carrier lifetime of GaAs/Si is almost the same as that of GaAs on GaAs substrate. The slopes are 1.89 and 2.02 ns, respectively, and about one order longer than that epitaxially-grown GaAs on Si substrate by the similar conditions.[10] This shows that the dislocation density of GaAs on Si by ELO and regrowth is almost the same as that grown on GaAs substrate.

Figure 4 shows the double crystal x-ray diffraction patterns of $GaAs/SeS_2/Si$ structure before growth (upper) and regrown GaAs on $GaAs/SeS_2/Si$ structure (lower). The FWHM is a little increased from 28 to 54 arc sec by the regrowth. But the crystal quality is still high compared with the heteroepitaxially grown GaAs on Si since the FWHM of heteroepitaxially grown GaAs on Si substrate is larger than 100 arc sec.[11] Since the broadening of FWHM is mainly due to the dislocations generated at GaAs/Si interface, the dislocation density of our film is very much improved compared with the heteroepitaxial GaAs-on-Si.

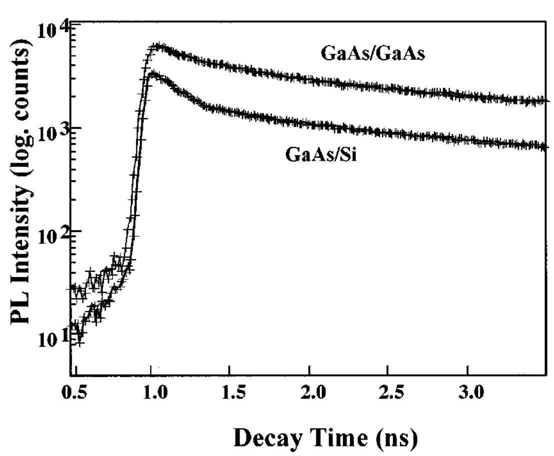

FIG. 3. Time resolved PL decay curves of GaAs grown on Si substrate by ELO and regrowth and GaAs grown on GaAs substrate.

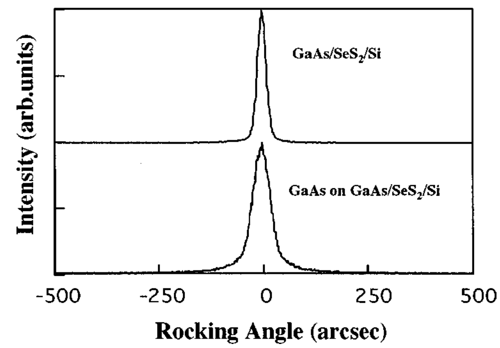

FIG. 4. Double crystal x-ray diffraction patterns of $GaAs/SeS_2/Si$ before regrowth (upper) and GaAs grown on $GaAs/SeS_2/Si$ (lower).

It is reported that the strain is not generated during the ELO process when the GaAs and Si are bonded using SeS_2 since the bonding is performed at low temperature.[6] This results in the superior optical and electrical properties compared with the heteroepitaxial GaAs-on-Si. It is also suggested that the strain is hardly generated even after the regrowth because the PL wavelength of GaAs/Si is almost the same as GaAs/GaAs. The stress relaxation would be considered to be due to strong bonding between GaAs and Si even at high temperature. It has been reported that the GaAs layer is bonded to Si substrate rigidly without generating stress or dislocation after ELO process.[6] X-ray photoelectron spectroscopy measurement reveals that the Ga–Se and Si–S bonds forming Ga_2Se_3 and SiS_2 phases are responsible for the strong bonding. Since the stress of GaAs thin film transferred to Si substrate is completely relaxed at room temperature and the GaAs layer is rigidly connected to Si, the compressive stress exists to the GaAs layer when the temperature of the wafer is raised to the temperature of regrowth (750 °C). The crystal regrowth takes place with the compressive stress to the GaAs layer. When the temperature of the sample is lowered to the room temperature after the regrowth, the stress applied to GaAs layer is relaxed at room temperature. The stress reduction would have produced such a high quality GaAs layer on Si substrate with a long minority carrier lifetime.

In summary, the stress-released GaAs layer was grown on Si substrate with the combination of ELO using SeS_2 and regrowth. The stress for the GaAs on Si substrate is very much reduced compared with the heteroepitaxial GaAs-on-Si. The effective minority carrier lifetime of GaAs-on-Si is almost the same as that for GaAs-on-GaAs. The high crystal quality is due to the strong bonding via Ga_2Se_3 and SiS_2 layers formed at the interface, which is stable at the growth temperature. The combination of ELO and regrowth is the way to obtain a device quality GaAs layer on a Si substrate.

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