THERMAL STABILITY OF HEAVILY CARBON-DOPED GaAs

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ABSTRACT

This paper investigates the effect of post-growth anneals (500°C-800°C) on the thermal stability of the carbon-doped structures. Hall measurements reveal that the hole concentration decreases steadily with increasing temperatures between 500°C and 800°C for all the heavily carbon-doped GaAs layer grown, which is attributed to the formation of passivated dicarbon C-C complexes on the As sub-lattice. Increases in hole mobility are observed in annealed layers due to lower carrier scattering as the room temperature hole mobility is dominated by ionized impurity scattering. The linear electro-optic (LEO) features observed in reflection anisotropy spectroscopy (RAS) in our heavily-doped samples did not show any change in width and amplitude when hole concentration decreases following anneals, presumably due to the smaller width of the depletion region than the light penetration depth. Raman spectroscopy showed no systematic variation of the LOPC line shape with carrier concentration due to heavy doping in our samples, which introduces a large damping constant.

Keywords: GaAs; Carbon-doped; Raman scattering; Reflection anisotropy

1. INTRODUCTION

The use of carbon as a p-type dopant in GaAs has attracted considerable interest recently because of its low diffusivity and high incorporation rate (10^{20}-10^{21} cm^{-3}) than zinc (Zn) and beryllium (Be), two commonly used p-type dopant in metal-organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) respectively [1-3]. Further more, even at these high concentrations, there is no evidence of carbon incorporated on Ga sites as donors [4]. Although the diffusion coefficient of carbon is known to be quite small, it is important to study the thermal stability of heavily carbon-doped GaAs, in particular the degradation of electrical and optical properties, because the material can be exposed to high temperatures in the process of device fabrication. Heavily carbon-doped GaAs layers are known to be unstable when annealed at high temperature after growth. As modern electronic devices become increasingly sophisticated and the trends are toward higher and complicated integration in their designs and productions, more stringent demands are placed upon the performance of these devices. Therefore, it is important that the behavior of carbon as a p-type dopant is well understood if it is to be widely use in III-V device applications.

2. EXPERIMENTAL PROCEDURE

The GaAs samples were grown using chemical beam epitaxy (CBE) specifically for the study of heavy continuous C-doping. The GaAs:C samples consist of nominally 500 nm carbon-doped layers grown on 250 nm undoped GaAs buffer layers on semi-insulating GaAs(001) substrates. Growth of the samples were carried out at a fixed temperature of 540°C with V:III ratios of !0:1 and carbon tetrabromide (CBr_4) line pressure of 0.5 torr. The expected acceptor concentration in GaAs for a CBr_4 line pressure of 0.5 torr is about $3x10^{20}$ cm^{-3}.

The electrical properties were studied using a Bio-Rad HL5200 Hall measurement system at room temperature. All measurements were carried out on samples using the Van der Pauw four-contact clover-leaf geometry. The Hall measurements allowed the simultaneous determination of the carrier concentration and Hall mobility of the as-grown and annealed carbon-doped layers.

All high temperature anneals were carried out in a Metritherm "theta 1450" tube furnace. Both ends of the tube were sealed and the system was purged for 20 minutes with flowing gas (Argon + 10% Hydrogen) prior to heating. Anneal time varied between one to four hours with temperature range between 500°C to 800°C.

RAS system was based on the photo-elastic modulated design reported by Aspnes et al. [5]. Raman measurements were made in the backscattering configuration with the spectra excited by the 514 nm line of an Argon ion laser operated at ~7mW. The optical penetration depth with this excitation is 126 nm. The scattered light was

analyzed by an 1800-lines/inch holographic grating and a CCD multichannel analyzer. The spectra resolution of the spectrograph was about 3 cm^{-3}.

3. RESULTS AND DISCUSSION

Fig. 1 shows the Hall carrier concentration following furnace annealing of the heavily C-doped GaAs samples. The "450°C" data represents the as-grown carrier concentration and mobility for no annealing. It is clear that the carrier concentration

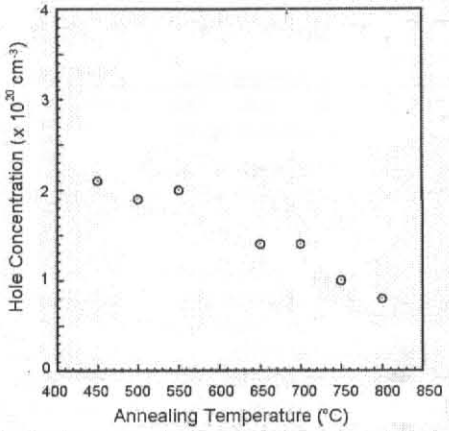

Fig. 1. Carrier concentration of carbon-doped GaAs after one-hour anneals. As-grown pre-anneal value is at 450°C.

decreases following increase in annealed temperature. The reduction in carrier concentration in GaAs:C has been associated with the formation of dicarbon C-C complexes [4]. At elevated temperatures C_{As} acceptors jump into interstitial sites. These C_i atoms are mobile and could be trapped by C_{As} atoms to form C-C split-interstitial pairs, which can act as donors or neutral complexes.

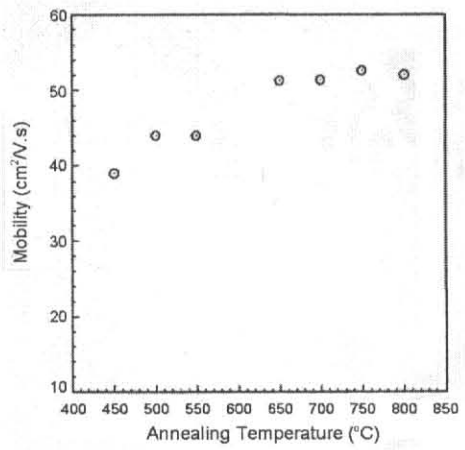

Fig. 2. Mobility of carbon-doped GaAs after one-hour anneals. As-grown pre-anneal value is at 450°C.

In Fig. 2, the Hall mobility showed a general trend of increases following increases in annealed temperature. The increases are presumably due to lower C_{As} concentrations after anneals resulting in less scattering, as the room temperature hole mobility is dominated by ionized impurity scattering.

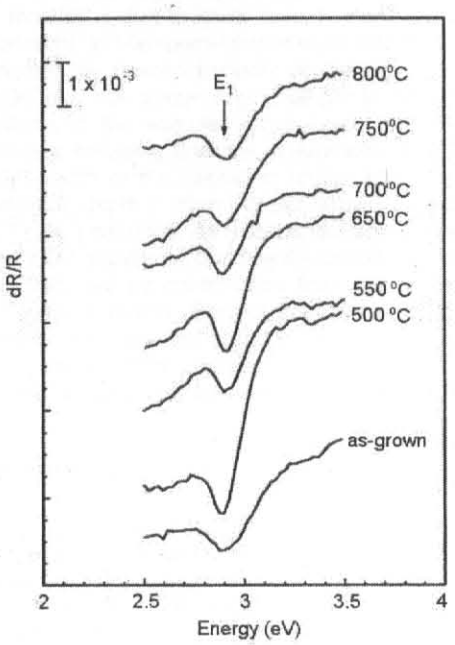

Fig. 3. RAS spectra of the carbon-doped p-type GaAs after one-hour anneals. Each spectrum is labeled with the annealed temperature.

Fig. 3 shows the reflection anisotropy spectroscopy (RAS) spectra (acquired with the incident polarization parallel to [100] so that the RA is between [110] and $[\bar{1}10]$) from the annealed carbon-doped GaAs samples. The spectra for all the annealed samples exhibit the same linear electro-optic (LEO) features with little variation from the as-grown sample. The position of the E_1 resonance for all the annealed samples is 2.9 eV, with very little change in width and amplitude. The LEO strength, which is manifested through the RA amplitude at the E_1 resonance, will have contributions from the depletion region over the entire light penetration depth (~ 20 nm in GaAs for light) near the E_1 energy. It is reported by Aspnes et al. [6] that the apparent surface electric field (SEF) determined by the LEO strength starts to deviate from the actual SEF when the depletion region is thinner than about 20 nm (the light penetration depth). Acosta-Ortiz et al. [7] reported that the amplitude of the RA LEO signal observed around the E_1 and $E_1+\Delta_1$ transition is reduced for lower doping levels. Their samples have low doping levels of only $3x10^{15}$ cm^{-3} and $1x10^{16}$ cm^{-3} (compared to ours at > $2x10^{20}$ cm^{-3}).

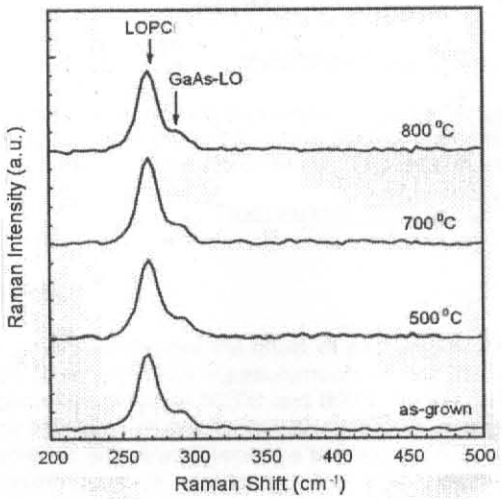

Fig. 4. Raman spectra for GaAs:C following one-hour anneals. Spectra are normalized to the intensity of GaAs-LO.

Raman spectra for annealed GaAs:C is shown in Fig. 4. The spectra are normalized to the peaks of the longitudinal-optical-phonon (LO-phonon) mode. It is clear that there is no significant difference between the intensities of the longitudinal-optical-phonon-plasmon-coupled (LOPC) signal even though hole concentration for the sample annealed to 800°C is half that of the as-grown sample. Peak position also remains near 268 cm^{-1} and the full-width at half maximum (FWHM) line-width of 17 cm^{-1} stays about the same for all samples. It was reported by Seon et al. [8] that their measurements for carbon-doped GaAs at very high carrier concentrations the LOPC line shape show no systematic variation with carrier concentration. In a doped sample, the plasmon damping constant Γ_p can be evaluated by the carrier scattering rate from the following expression:

$$\Gamma_p = \frac{e}{\mu_h m_h}$$

where e is the electrical charge, μ_h and m_h are the effective mass and mobility of the free carriers. The lower hole mobility due to heavy doping in our samples introduces a large damping constant such that the strongly damped plasmon cannot interact well with the LO-phonon. This may explain the lack of any systematic correlation (in intensity and line-width) in the LOPC mode with changes in carrier concentration for our highly doped ($p > 2 \times 10^{20}$ cm^{-3}) samples.

4. CONCLUSION

The thermal stability of heavily carbon-doped GaAs has been systematically investigated. It was found that hole concentration for the carbon-doped samples decreases for all annealing temperatures from 500°C – 800°C. The reduction in hole concentration is associated with the formation of passivated dicarbon C-C complexes on As sublattice sites. Hall mobility for most samples showed slight increases to that of the as-grown layers for the same range of annealing temperatures. The increase in hole mobility is due to lower hole concentration after the anneals as the room-temperature hole mobility is dominated by ionized impurity scattering. The LEO signals did not show any change in width and amplitude in the samples when hole concentration decreases following anneals, presumably due to the smaller width of the depletion region than the light penetration depth (~20nm) in our heavily doped ($p > 2x10^{20}$ cm^{-3}) samples. As a result, the actual strength of the LEO signals in our heavily-doped samples is being distorted by contribution from region beyond the depletion region. Raman spectroscopy showed no systematic variation of the LOPC line shape with carrier concentration due to heavy doping in our samples, which introduces a large damping constant.

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