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Metastable Properties of the Dominant Electron Trap in Low-Temperature GaAs Grown by Molecular Beam Epitaxy

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Photocapacitance transient behavior of the dominant S1 electron trap (Ec-0.64eV) in MBE-grown LT-GaAs, which we recently detected by DLTS method, was investigated in detail. It was found that the S1 trap has metastable properties causing marked photoquenching behavior. Transition processes between the ground state and the metastable state were found to be very different from those of EL2, indicating that the dominant S1 trap is not EL2, but a new deep level peculiar to the LT-GaAs layer.

1. Introduction

Undoped GaAs layers grown by molecular beam epitaxy (MBE) at low substrate temperatures or the so-called LT-GaAs buffer layers have attracted considerable attention because they eliminate the sidegating effects in MESFETs and HEMTs as well as they realize ultrahigh-speed photodetectors. However, the mechanism for their unique semi-insulating properties have not been clarified yet. We have recently found that the electron trap, S1, with an activation energy of 0.64 eV acts as a dominant center for semi-insulating properties of LT-GaAs.[1]

The purpose of the present paper is to investigate the photocapacitance behavior of the dominant electron trap S1 in MBE grown LT-GaAs. It is shown that the dominant electron trap S1 exhibits marked photoquenching behavior. A detailed analysis has shown that the transition processes between the ground state and the metastable state of the S1 trap is very different from that of EL2.

2. Experimental

The sample structure used in the present study is schematically shown in **Fig.1.** Al Schottky diodes were fabricated on the Si-doped LT-layers by vacuum evaporation and In metal prepared at the backside of n^+ substrates for MBE growth was used as an ohmic contact.

LT-GaAs layers were grown on n^+-GaAs substrate at 250-400°C in a standard MBE system. The thickness of the layer is typically 1μm. After LT-growth, all the samples were annealed at 580°C in the MBE chamber under arsenic over pressure. Conductive layers with a carrier concentration of 1×10^{16}-$2\times10^{17}cm^{-3}$ were achieved by Si-doping at Tg>300°C with the activation efficiency rather rapidly reducing with the reduction of the growth temperature. The layers grown at 250°C exhibited semi-insulating properties even when the intended Si-doping density of $3\times10^{18}cm^{-3}$.[1]

Experimental sequence for photo-capacitance (PHCAP) measurements is shown in **Fig.2.** Al/LT-GaAs Schottky samples were cooled from room temperature to the measurement temperatures (T_{meas}) under a forward bias condition, keeping the traps being occupied by electrons. Then, the bias was changed stepwise to a reverse value and the capacitance transient was measured under illumination, as shown in Fig2. GaAs LED (hv= 1.34eV) and Xe lump were used as light sources and the capacitance transients were recorded using a capacitance meter (HP 4280A).

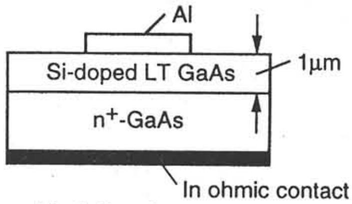

Fig.1. Sample structure.

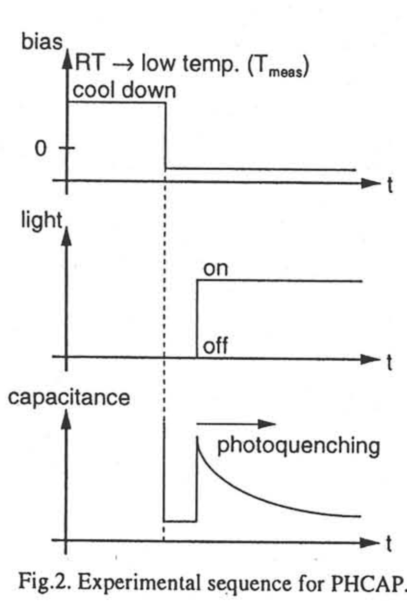

Fig.2. Experimental sequence for PHCAP.

3. Results and discussion

3.1 Photoquenching behavior of the S1 trap

Our previous DLTS study[1)] detected five electron traps in the Si-doped LT-GaAs layers grown at 300-400°C as shown in **Fig.3**. As seen, the dominant trap was found to be the S1 trap whose energy level lies at Ec-0.64eV. The concentration of the S1 trap rapidly increased as the growth temperature Tg was reduced, while the concentrations of other traps remained more or less the same with Tg. From the comparison of the signature plots for five observed electron traps in LT-GaAs with those of the known traps in bulk and epitaxial GaAs materials,[2-5)] the S1 trap was found to have the plot close to those of EB3 and/or EB4.

In order to gain information on the structural configuration of the electron traps in LT-GaAs, a PHCAP measurements were carried out. **Figure 4** shows the measured PHCAP transient curves of the Si-doped LT-GaAs layer grown at 350°C for various measurement temperatures. The curves showed a clear photoquenching of capacitance below 110K. The transient was found to follow a simple exponential form as shown in **Fig.5**. The trap density estimated from the magnitude of transient capacitance agreed with the concentration of the S1 trap determined by the DLTS measurement, indicating that the S1 trap is responsible for the observed photoquenching. Thus, the dominant S1 trap has a metastable state which presumably reflects presence of a large lattice relaxation in its close environment.[6,7)]

3.2 Thermal recovery process

The amplitude of capacitance quenching decreased with the increase of temperature, and this can be explained in terms of the thermal recovery of electrons from the metastable state to the ground state at higher temperatures.

Then, the thermal recovery rates can be determined from the capacitance recovery during a light-off time interval, Δt_R, as shown in the inset of **Fig. 6**, where the ratio of the initial quenching capacitance ΔC_Q to the quenching capacitance ΔC_R obtained after Δt_R, is plotted vs. Δt_R. **Figure 7** shows the thermal recovery rate, r, thus measured vs. reciprocal temperature. The energy barrier height (ΔE_B) for recovery from the metastable state to the ground state of the S1 trap was estimated to be 0.06eV. This value is much smaller than that of the well-known EL2 level (ΔE_B = 0.35-0.40eV).[7)] Similar small values of ΔE_B have been observed in GaAsP[8)] and AlGaAs[9)] alloys and intentionally oxygen-doped LEC GaAs[10)]. This reflects different situations in lattice relaxation for various material systems.

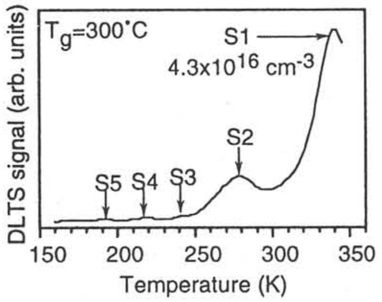

Fig.3. DLTS spectrum obtained from the LT-GaAs layer grown at 300℃.

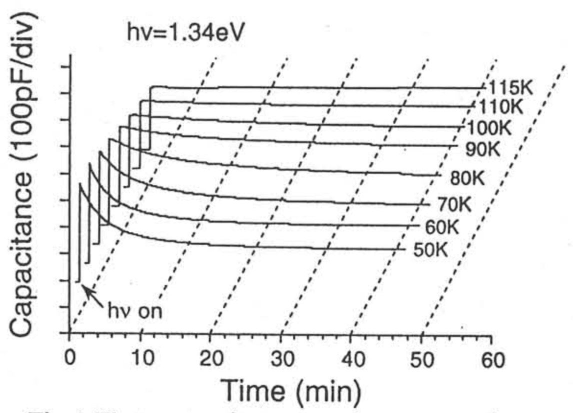

Fig.4. Photo-capacitance transient curves of LT-GaAs layer for various temperatures.

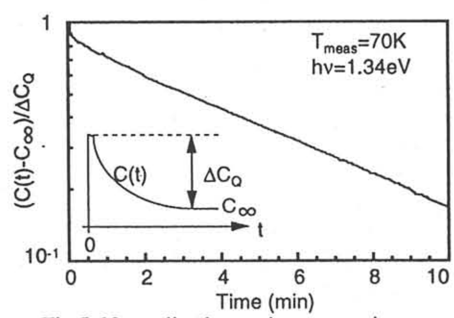

Fig.5. Normalized capacitance transient on logarithmic scale.

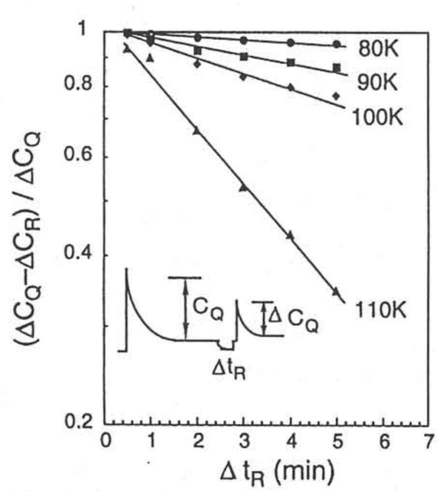

Fig.6. Plots of the normalized capacitance recovery.

3.3 Photon-energy dependence of the photoquenching rate

Figure 8 shows capacitance transients at 70K under illumination with various wavelengths of illumination. The results clearly showed that transition probability from the ground state to the metastable state depends on the photon energy. From the time constant of capacitance quenching, the photon-energy dependence of the transition rates to the metastable state was determined, as shown in **Fig. 9**. For comparison, transition rates in VPE-GaAs and HB-GaAs are also plotted in Fig.9.

The shape of the photon-energy dependence of the transition rate is rather similar among three materials. However, values of the rates for LT-GaAs are lower than those of VPE and HB-GaAs by a factor of 5-10.

3.4 Discussion

The photoquenching effect is believed to take place by a successive transfer of electrons from the ground state to the metastable state through an excited state lying at higher energy level. Thus, both the photon-energy dependence of transition probability and the thermal recovery behavior observed for the LT-GaAs clearly indicate that transition processes within the S1 trap are different from those of the EL2 level. The dominant S1 trap is not EL2, but a new deep level peculiar to the LT-GaAs layer. In addition, all the DLTS and PHCAP results indicate that the mechanism responsible for semi-insulating property of undoped LT-GaAs layer is due to deep level compensation by a high density of the S1 trap, and not by As-precipitate-induced Fermi level pinning.[11)]

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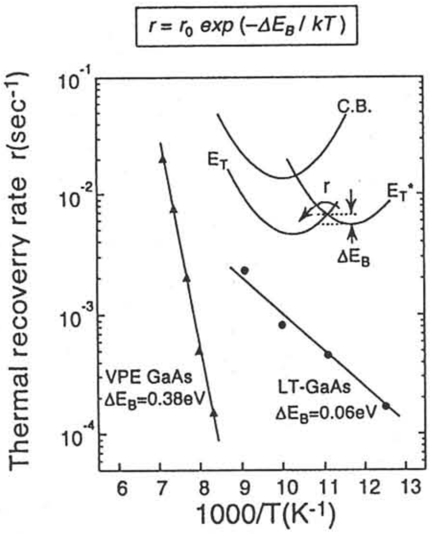

Fig.7. Thermal recovery rate as a function of reciprocal temperature.

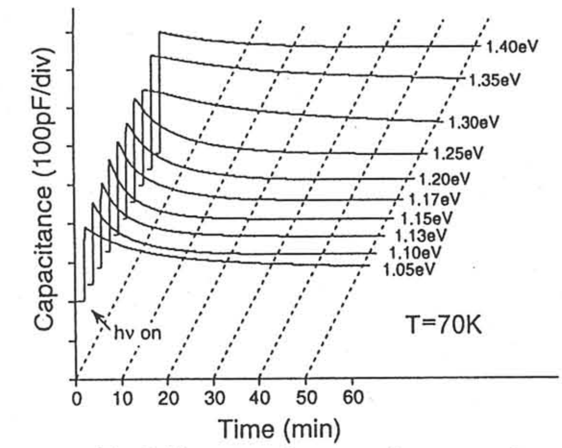

Fig. 8. Photo-capacitance transient curves of LT-GaAs layer for various wavelength.

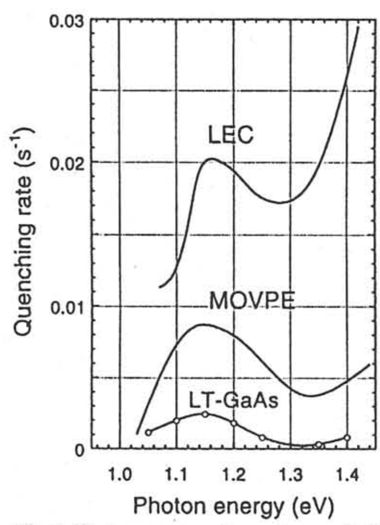

Fig.9. Photon-energy dependence of the quenching rate.