Effects of High-Resistivity, Low-Temperature Layer in Transient Capacitance Measurements

of GaAs n-i-p Structures

Effects of High-Resistivity, Low-Temperature Layer in Transient Capacitance Measurements of GaAs n-i-p Structures

Jenn Fang CHEN, Pai Yong WANG and Nie Chuan CHEN

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

Deep-level transient spectroscopy and transient capacitance measurements are performed on a molecular-beam-epitaxially grown GaAs n-i-p diode with a 2000-Å-thick low-temperature (LT)-grown layer immersed in its intrinsic region. The transient capacitance measurements reveal that the time constant and activation energy are the same for both the emission and capture processes. An equivalent circuit based on capacitance-frequency spectra is derived and used to obtain the resistivity values of the LT layer that are in agreement with experimental results. It is concluded that the transient capacitance observed corresponds to the resistance-capacitance time constant due to the LT-layer. In addition, the value of the activation energy is explained based on the equivalent circuit.

KEYWORDS: low-temperature GaAs, deep-level transient spectroscopy, transient capacitance, deep levels

Low-temperature (LT) grown GaAs has drawn much attention because of its high resistivity,[1-3] relatively high mobility[4] and ultra short photo carrier lifetime.[5,6] A high concentration of As_{Ga} defects[1] or arsenic precipitates[7] has accounted for these properties. Among many different measurement techniques, deep-level transient spectroscopy (DLTS) is a useful technique for defect characterizations. Several groups have used it to study the defect levels in LT GaAs, but the observed values of activation energy and capture cross section are usually not consistent with each other, partly due to the effect of the high-resistance LT layer, the properties of which are usually affected by growth parameters such as growth temperature, beam equivalent pressure, and annealing conditions. There exists a lack of understanding about the effects of the LT layer on deep-level characterizations. To illustrate this, we perform DLTS and transient capacitance measurements on a n-i-p diode with a LT layer immersed in the intrinsic region. The results are analyzed based on an equivalent circuit derived from the frequency-capacitance spectra in order to show the effects of the high-resistivity LT layer when interpreting the data.

The LT sample is a p-i-n GaAs diode, consisting of $1\,\mu m$ n($5 \times 10^{17}\,cm^{-3}$)/$0.2\,\mu m$ undoped LT/$0.6\,\mu m$ undoped/p($10^{17}\,cm^{-3}$), grown on (001) n$^+$-GaAs substrate using a Varian Gen-II molecular beam epitaxy (MBE) system. The LT layer was grown at 300°C. On top of the p layer, a heavily doped $0.5\,\mu$m-thick p$^+$ ($>5 \times 10^{18}\,cm^{-3}$) cap layer was grown to facilitate a good ohmic contact. After the LT growth, the substrate temperature was raised to 600°C for growth of the rest of the layers, thus the LT layer was subsequently annealed for about 1 hour. For comparison, a reference sample with the same structure as that of the p-i-n LT sample, except that the $0.2\,\mu$m undoped LT layer for the LT sample was also grown at the normal temperature of 600°C, was subsequently grown. In other words, this reference sample has a $0.8\,\mu$m-thick i layer. Both the LT and the reference samples were grown under a beam equivalent pressure ratio of As$_4$ to Ga of about 10 and a growth rate of $1\,\mu$m/h.

The DLTS spectra for the LT and reference samples are shown in Fig. 1. The measurements were performed at 500 kHz and carriers were injected by applying a forward bias of 0.3 V and then depleted at −3 V. It can be seen from Fig. 1 that there is no significant signal for the reference sample,
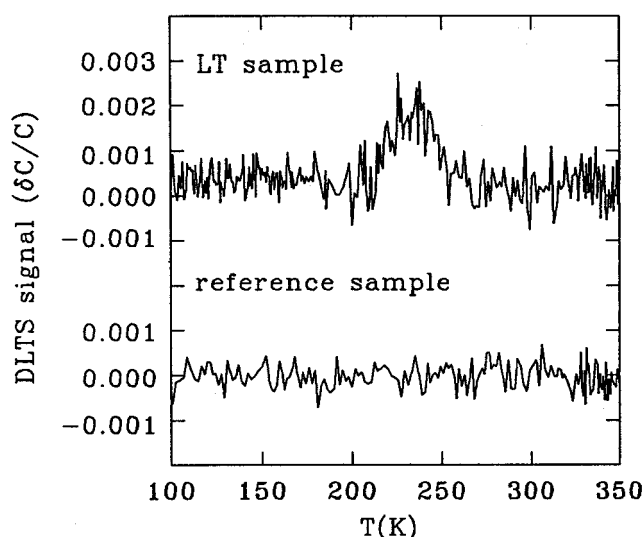

Fig. 1. DLTS spectra of the LT and reference samples at a time constant of 0.9 s. The LT sample reveals a weak deep-level signal.

while a weak signal ($\Delta C/C \approx 0.002$) around 250 K is seen for the LT sample. Since the signal was not observed in the reference sample, it must be related to the LT layer. Due to the signal being weak, we were not able to determine the parameters of the LT sample. Therefore, we directly recorded the emission response of the LT sample at 500 kHz, by first maintaining the sample at 0.2 V, and then changing to −2.5 V for the measurement. The result is shown in Fig. 2(a) along with $\delta C(t)/\delta C(0)$ in the inset for a least square fit of its time constants. At the same time, we also recorded the capture response, by first maintaining the sample at −2.5 V and then changing to 0.2 V. The result is shown in Fig. 2(b) along with its $\delta C(t)/\delta C(0)$ in the inset.

Figure 2 illustrates the following features: (1) the emission process behaves as a minority carrier trap, (2) the emission and capture transient responses have similar magnitudes, (3) the capture time constant τ is equal to the emission time constant, and (4) the emission and capture processes exhibit a similar activation energy of about $E_a = 0.35 \pm 0.02\,$eV, indicating that both processes must overcome the same barrier. The activation energy was obtained by the slope of the temperature-corrected emission (capture) rate τT^2 versus the
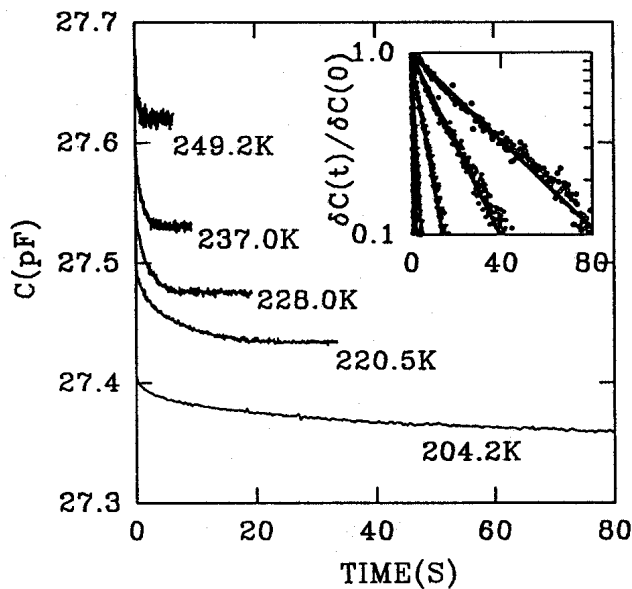
(a)
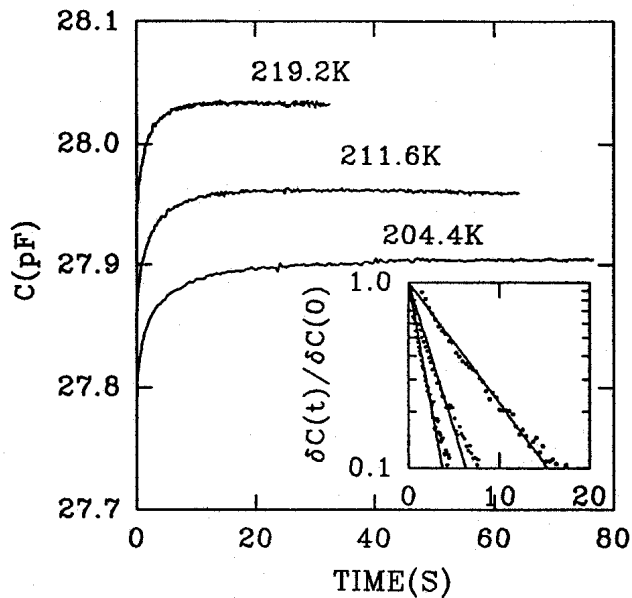
(b)

Fig. 2. (a) Emission capacitance transient for the LT sample along with its $\delta C(t)/\delta C(0)$ in the inset. The transient shows a minority carrier trap with an activation energy of 0.35 eV. (b) The corresponding capacitance transient. The time constant and activation energy are the same for both emission and capture processes.

inverse temperature $1000/T$.

Here, we examine three possible explanations for the above features. The first explanation is based on the value of E_a. The LT GaAs is known to have a V_{Ga} Ga vacancy, which was reported at about 0.3 eV above the valence band by Fang and Look[8] and Witt.[9] Although the values reported by them are similar, we consider this explanation unlikely because a normal defect should not have a significant capture barrier. It is even unlikely that the emission barrier is the same as the capture barrier. Therefore, we rule out this possibility.

The second explanation is based on the fact that both the emission and capture processes have the similar barrier. In the As precipitate model, a Schottky depletion region was be-

lieved to surround the As precipitate[7] in LT GaAs. This could lead to both processes having the similar barrier. However, the E_a value (=0.35 eV) is much lower than the typically believed barrier of 0.7–0.8 eV. Moreover, each As precipitate is likely to capture more than one electron. If the capture barrier is due to the electric field created by the already captured electrons, the barrier height ϕ_B should be proportional to the number of captured electrons n_t, that is $q\phi_B = \alpha n_t$, where α is a proportional constant. Therefore, the time variation of n_t can be expressed as

$$\frac{dn_t}{dt} = \sigma_n v_{th} n \, e^{-\frac{q\phi_B}{KT}} = \sigma_n v_{th} n \, e^{-\frac{\alpha n_t}{KT}},$$

where α_n is the capture cross section, v_{th} is the thermal velocity and n is the free electron concentration, and $n_t(t)$ is solved as

$$n_t(t) = \frac{KT}{\alpha} Ln\left(\frac{t+\tau}{\tau}\right),$$

where

$$\tau = \frac{KT}{\alpha \sigma_n v_{th} n}.$$

From this equation, the number of electrons being captured by As precipitate depends on time, indicating that the capture transient should be a log function with a behavior similar to that observed for dislocation core[10] instead of an exponential function. However, this is contradictory to what is shown in Fig. 2. Therefore, we also rule out the explanation that the Schottky depletion model gives rise to the observed transient responses.

The third explanation come from the fact that the LT layer is highly resistive. This high-resistivity layer causes a resistance-capacitance (RC) effect which is irrelevant to forward or reverse bias. This will result in the emission time constant being equal to the capture time constant. In order to verify this origin, we need to determine the equivalent circuit for the LT sample. Figure 3 shows the capacitance-frequency C-f spectra measured for the LT sample. The spectra demonstrate two C steps: the low-frequency step (from ≈ 120 to ≈ 40 pF) and the high-frequency step (from ≈ 40 to ≈ 30 pF). The high-frequency step corresponds to the RC time constant due to the LT layer and can be represented by an equivalent circuit, as shown in Fig. 3. A detailed explanation of these C-f spectra has been given elsewhere.[11] The LT layer is represented by a resistance R in parallel with a parallel-plate capacitor of $C_1 = \frac{A\varepsilon}{d} \cong 120$ pF with d being equal to the thickness of the LT layer (0.2 μm). This circuit is in series with a capacitor of $C_2 = \frac{A\varepsilon}{d'} \cong 40$ pF with d' being equal to the thickness of the intrinsic layer (0.6 μm). This equivalent circuit has a high-frequency capacitance of

$$\frac{C_1 C_2}{C_1 + C_2} \cong 30 \, pF$$

with a time constant of $\tau = R(C_1 + C_2)$. This equivalent circuit should give rise to the observed emission and capture transient responses. From the transient time constants observed in Fig. 2, using $\tau = R(C_1 + C_2)$, values of R can be obtained at various temperatures, as shown in Fig. 4 by hollow squares for the emission transient and solid squares for the capture transient. We found that their values are consistent with those of LT resistance, previously determined from C-ω measurements.[11] Moreover, we have previously studied the
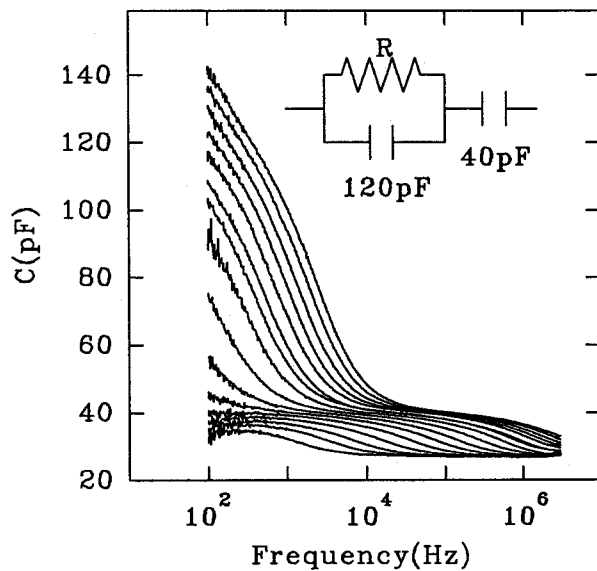
Fig. 3. The capacitance-frequency spectra for the LT sample. The temper-atures for each curve are 300.2, 310.8, 319.5, 329.8, 340.2, 350.0, 360.0, 370.0, 380.1, 385.3, 390.0, 395.3, 400.2, 405.0, 410.1, and 414.4 K from bottom to top. The spectra show two C steps with the emission rate of the high-frequency step ($C = 40$ to 30 pF) corresponding to the RC time constant due to the LT layer[11] and is represented by an equivalent circuit.
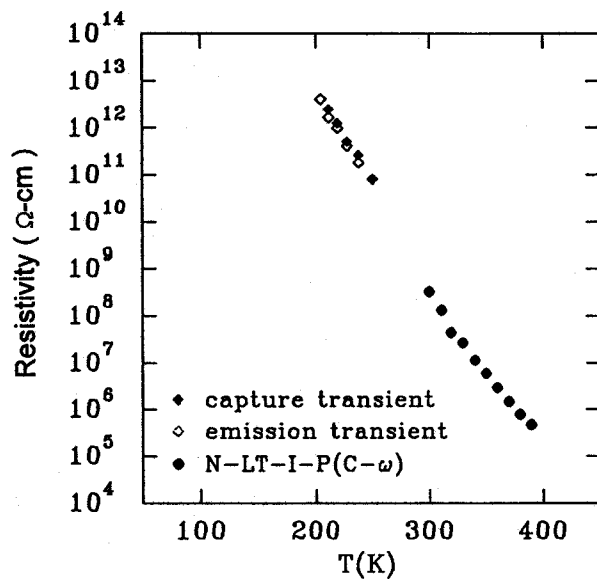

Fig. 4. The resistivity values of the LT layer derived from the time constant of the high-frequency C step in Fig. 3 (shown as solid circles), which are in agreement with those directly measured from LT layers in n$^+$-LT-n$^+$ structures.[3] The resistivity values derived from the emission transient (the hol-low squares) and from the capture transient (the solid squares) are shown to be consistent with the resistivity values of the LT layer.

resistivity of the LT layer by measuring the current-voltage-temperature characteristics of n$^+$-LT-n$^+$ structures.[3] The resistance values shown in Fig. 4 are also in agreement with those measured from n$^+$-LT-n$^+$ structures. This agreement supports the conclusion that the $R(C_1 + C_2)$ time constant due to the high-resistivity LT layer gives rise to the observed transient responses in DLTS and transient capacitance mea-surements and that the corresponding activation energy value observed is in agreement with that of the resistivity of the LT layer.

Here, we explain why a value of 0.35 eV was measured for the activation energy. Based on the current-voltage character-istics of the n$^+$-LT-n$^+$ structures,[3] the conductivity of the LT layer changes from a band conduction ($E_a = 0.72$ eV) to a hopping conduction when $T < 250$ K. The hopping conduc-tion reduces the activation energy. Therefore, the E_a value depends on the temperature at which the transient response is observed, which in turn depends on the rate window used. Since the transient response was observed at $T < 250$ K the hopping conduction effect cannot be neglected. This explains why the activation energy value observed is 0.35 eV instead of about 0.7 eV.

Finally, we discuss why the emission transient behaved as a minority carrier trap in Fig. 2(a). The measurement was performed at 500 kHz; at this frequency the capacitance is the parallel capacitance of C_1 (120 pF) and C_2 (40 pF), as shown in Fig. 3. Its variation with bias is

$$\delta C = \delta \frac{C_1 C_2}{C_1 + C_2} = \frac{C_2^2}{(C_1 + C_2)^2} \delta C_1 + \frac{C_1^2}{(C_1 + C_2)^2} \delta C_2.$$

Figure 3 shows that the time constant of δC_1 (the low-frequency C step) is too large to follow the measuring signal at 500 kHz. Therefore, the first term in the above equation is neglected and the capacitance variation is dominated by δC_2. Since δC_2 decreases with increasing reverse bias, as shown in Fig. 6 in ref. 11, the transient capacitance decreases in the emission process and exhibits a minority carrier trap.

1) D. C. Look, D. C. Walters, M. O. Manasreh, J. R. Sizelove, C. E. Stutz and K. R. Evans: Phys. Rev. B **42** (1990) 3578.
2) F. W. Smith, H. Q. Le, V. Diadiuk, M. A. Hollis, A. R. Calawa, S. Gupta, M. Frankell, D. R. Dykaar, G. A. Mourouu and T. Y. Hsiang: Appl. Phys. Lett. **54** (1989) 890.
3) J. F. Chen, N. C. Chen, S. Y. Chiu, P. Y. Wang, W. I. Lee and A. Chin: J. Appl. Phys. **79** (1996) 8488.
4) D. C. Look, G. D. Robinson, J. R. Sizelove and C. E. Stutz: Appl. Phys. Lett. **62** (1993) 3004.
5) K. A. Mclntosh, K. B. Nichols, S. Verghese and E. R. Brown: Appl. Phys. Lett. **70** (1997) 354.
6) S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith and A. R. Calawa: Appl. Phys. Lett. **59** (1991) 3276.
7) A. C. Warren, J. M. Woodall, J. L. Freeouf, D. Grischkowsky, D. T. Mclnturff, M. R. Melloch and N. Otsuka: Appl. Phys. Lett. **57** (1990) 1331.
8) Q. Fang and D. C. Look: Appl. Phys. Lett. **63** (1993) 219.
9) G. L. Witt: Mat. Sci. Eng. B **22** (1993) 9.
10) T. Wosinnski: J. Appl. Phys. **65** (1989) 1566.
11) N. C. Chen, P. Y. Wang and J. F. Chen: J. Appl. Phys. **83** (1998) 1403.