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Quick measurement method of carbon-related defect concentration in n-type GaN by dual-color-sub-bandgap-light-excited isothermal capacitance transient spectroscopy

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Abstract

We propose a quick measurement method of the carbon-related hole trap (H1, E_V+0.87 eV) concentration in n-type GaN by dual-color-sub-bandgap-light-excited isothermal capacitance transient spectroscopy (dual-color-sub-E_g-light ICTS). Shorter wavelength light irradiation is carried out to make the hole trap to be hole-occupied state. Then, longer wavelength light irradiation is carried out to emit the hole from the trap to the valence band. The trap concentration can be calculated from the capacitance change.

1. Introduction

Reducing deep levels is essential to fabricate high performance GaN-based devices. In metalorganic vapor phase epitaxy (MOVPE)-grown n-type GaN layers, (1) the hole trap H1 (E_V+0.87 eV) was detected as a dominant minority carrier trap [1,2] and (2) its origin is most likely the residual carbon from metalorganic source [$(CH_3)_3Ga$] substituting at the nitrogen site [C_N (-/0)] [1-3]. Thus, reduction of the H1 trap concentration (N_T) is very important. Development of a measurement method of N_T is very important to obtain quick feedback for optimization of the growth conditions. In our previous study, we developed a determination method of N_T in n-type GaN layers by changing measurement conditions of sub-bandgap-light-excited isothermal capacitance transient spectroscopy (sub-E_g-light ICTS) using Schottky barriers [4]. However, the proposed method is time-consuming because of the long time constant of hole thermal emission (τ_p^t) from the H1 trap (ex. τ_p^t~30 s at 300 K). In this study, we propose a quick measurement method of N_T in n-type GaN by dual-color-sub-E_g-light-excited ICTS. In the method, shorter wavelength light is irradiated to make the hole trap to be hole-occupied state. This is the same as our previous proposed method. Then, longer wavelength light irradiation is carried out to emit the hole from the trap to the valence band. Compared with thermal emission, the photoexcited emission is much faster, resulting in great reduction of measurement time.

2. Experimental method

An MOVPE-grown 3-μm-thick n-type GaN on a quarter of a 2-inch HVPE-grown n^+-type GaN substrate was used. Ni-Schottky contacts were formed on the n-type GaN layer. The Si and C concentrations ([Si] and [C]) measured by SIMS are

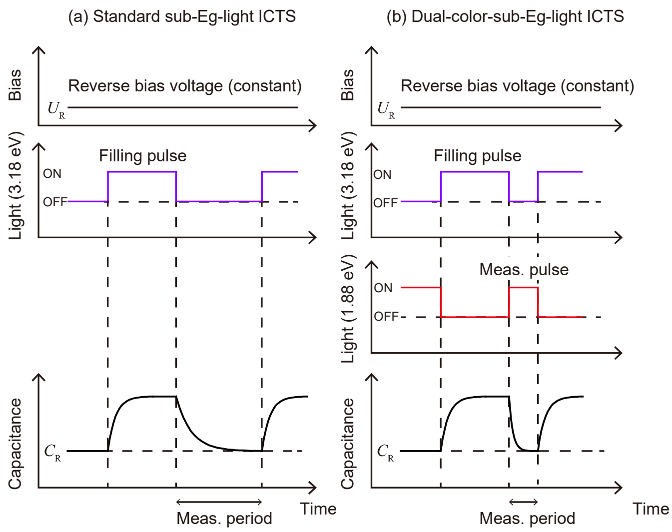

Fig. 1. Measurement sequences of (a) standard sub-E_g-light ICTS and (b) dual-color-sub-E_g-light ICTS, in which 1.88 eV light is irradiated during measurement period for quick hole photoexcitation.

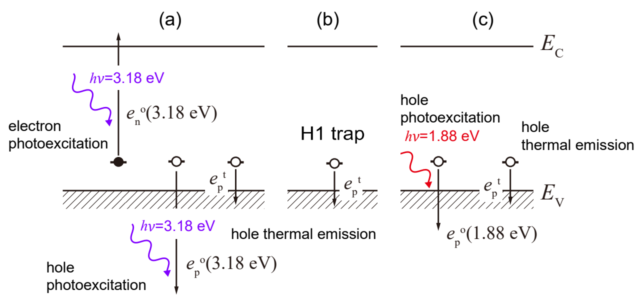

Fig. 2. Band diagram of the H1 trap in n-type GaN during (a) filling pulse period and measurement period in (b) standard and (c) dual-color sub-E_g-light ICTS, respectively.

3.0×10^{16} cm^{-3} and 2×10^{15} cm^{-3}, respectively. In our previous study, it was shown that N_T is 2.3×10^{15} cm^{-3} and the H1 trap is mainly associated with C_N (-/0) in the epilayer [4].

In Fig. 1, the measurement sequences of (a) our previously-proposed standard sub-E_g-light ICTS and (b) dual-color-sub-E_g-light ICTS are shown. As shown in Fig. 2 (a), electron and hole photoexcitation and hole thermal emission occur during filling pulse period (shorter wavelength light excitation period). The H1 traps are filled by holes at a hole occupancy ratio (f_T) which is determined by the competition among the three processes. After then, during measurement period, the holes are emitted from the H1 traps to the valence band at a hole emission rate (e_p=1/τ_p, τ_p: time constant of hole emission). In standard sub-E_g-light ICTS, the holes are only thermally emitted at hole thermal emission rate (e_p^t=1/τ_p^t) and it is shown in Fig. 2 (b). On the other hand, during measurement period in dual-color-sub-E_g-light ICTS photoexcitation (longer wavelength light irradiation period), the holes are emitted by both thermally and optically as shown in Fig. 2 (c). Thus, e_p is a sum of e_p^t and hole photoexcitation rate (e_p^o).

In this study, 390 nm (3.18 eV) LEDs and 660 nm (1.88 eV) LEDs are employed as the light sources of filling and measurement pulses, respectively. As shown in Fig. 2 (a) and (c), electrons and holes are photoexcited by irradiation at photon energy of 3.18 eV. On the other hand, only holes are photoexcited by irradiation at 1.88 eV because of the photoionization energy of 2.95 eV for C_N (-/0) [3]. Sub-E_g-light ICTS was performed at the constant reverse bias voltage (U_R) from -2 V to -10 V at 300 K.

3. Results and discussion

In Fig. 3, the black solid line is standard sub-E_g-light ICTS spectrum and e_p^t of 0.03 s^{-1} is obtained. The red solid line in Fig. 3 is spectrum of dual-color-sub-E_g-light ICTS and $e_p^t + e_p^o$ is obtained. e_p^o of 0.63 s^{-1} is extracted by using $e_p^t + e_p^o$ and e_p^t under this measurement condition. e_p^o is around 20 times larger than e_p^t and it makes quick measurement of the H1 trap at 300 K to be possible.

The detected H1 trap concentration by sub-E_g-light ICTS ($\widetilde{N}_T$) is a production of N_T, f_T, and the depletion layer edge factor (F) [4]. From dual-color-sub-E_g-light ICTS at various U_R, the dependence of $\widetilde{N}_T$ on the depletion layer width was obtained and it is shown in Fig. 4. By considering the depletion layer edge correction [5], the hole-occupied H1 trap concentration during the filling pulse period ($f_T N_T$) of 1.7×10^{15} cm^{-3} was obtained and this value is in a good agreement with the $f_T N_T$ of 1.7×10^{15} cm^{-3} obtained by standard sub-E_g-light ICTS at 300 K which is performed under the same condition of filling pulse. Thus, f_T should be the same and the result is reasonable. Using f_T of 0.7 [4], N_T of 2.2×10^{15} cm^{-3} was determined and showing good agreement with N_T of 2.3×10^{15} cm^{-3} the previous method and [C] of 2×10^{15} cm^{-3} in the n-type GaN layer.

4. Conclusions

In this study, we propose a quick measurement method of the H1 trap concentration by dual-color-sub-bandgap-light-excited ICTS. Compared with our previously-proposed method, the quick measurement method reduces the measurement time by over 10%. The method is useful for the wafer mapping measurement of the H1 trap concentration.

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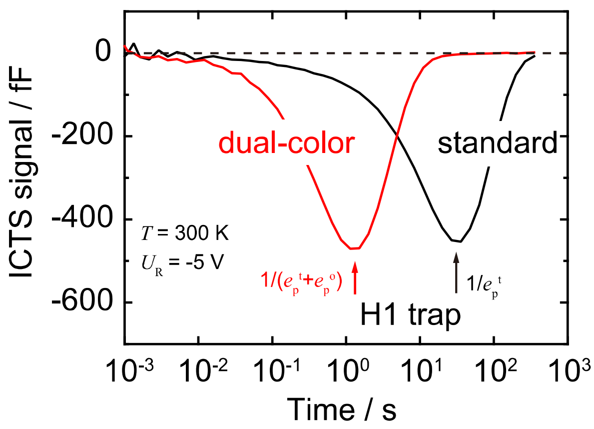

Fig. 3. Sub-E_g-light ICTS spectra at U_R = -5 V and 300 K. The black solid line is spectrum without optical pulse during measurement period, which is standard method. The red solid line is spectrum with optical pulse during measurement period, which is dual-color method. The time constants of hole emission are 33 s for "standard" and 1.5 s for "dual-color".

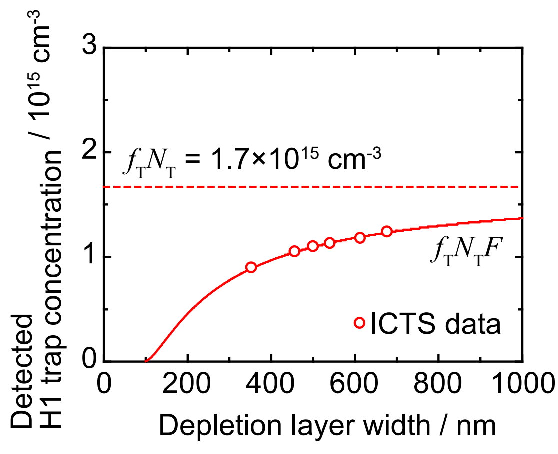

Fig. 4. Dependence of detected H1 trap concentration by dual-color-sub-E_g-light ICTS on depletion layer width. The detected H1 trap concentration is shown as the circle symbols and calculation result is shown as the solid line. Considering the depletion layer edge correction, hole-occupied H1 trap concentration of 1.7×10^{15} cm^{-3} is determined.