Bestelldatum: 2009-29-10 09:03:16
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Signatur: **85 85/UA 4210.1**
Titel Zeitschrift / Werk: **Japanese journal of applied physics / 1**

Band / Heft: **40**
Ersch.-Jahr: **,2001**
Seiten: **5871-5874**
Aufsatztitel:

Autor (Artikel):
Autor / Hrsg. (Werk):
Ort / Verlag: **: Tokyo,Oyo Butsuri Gakkai**
ISSN / ISBN: **0021-4922**
Kundenspezifische Infos: ,

Kontaktperson/Bemerkung: Ms Izabela Ohanyan

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Jpn. J. Appl. Phys. Vol. 40 (2001) pp. 5871–5874
Part 1, No. 10, October 2001

Long-Term Photocapacitance Decay Behavior in Undoped GaN

Hao-Ming CHUNG, Yung-Chung PAN, Wang-Chung CHUANG, Nie-Chuan CHEN, Cheng-Chung TSAI, Ming-Chih LEE, Wen-Hsiung CHEN and Wei-Kuo CHEN

Department of Electrophysics, National Chiao-Tung University, Hsin-Chu, Taiwan 300, R.O.C.

(Received September 25, 2000; revised manuscript received May 7, 2001; accepted for publication June 14, 2001)

We have measured the dynamic response of the photocapacitance of a Schottky diode made of an undoped GaN epilayer grown by metalorganic vapor phase epitaxy. The measurements were performed after the suspension of a white light for a specified "waiting" time, t. The results indicate that the capacitance exhibits a logarithmic function of t from which a time constant of approximately 34.5 s and a cross-sectional area of less than 2.89×10^{-27} cm^2 were retrieved. These are interpreted as the characteristic time and the cross-sectional area of electron capture by the traps associated with dislocations formed in the epifilm, respectively.

KEYWORDS: GaN, photocapacitance, logarithmic, decay, dislocations, MOVPE

1. Introduction

Because of its superior material properties including a wide direct band gap, high breakdown electric field, and high thermal conductivity as well as high thermal stability, gallium nitride (GaN) has recently drawn much attention from the view point of use in a variety of device applications. These include high-temperature transistors,[1] blue and green light-emitting diodes and violet laser diodes.[2] However, as compared to GaAs and InP, GaN usually possesses relatively poor film quality in terms of dislocations. With such a high density of threading edge dislocations[3] (10^8 cm^{-2}), it was difficult to believe that high-performance optoelectronic devices can be realized without difficulty by the use of this type of material. In the early stages of GaN device fabrication, researchers even believed that the dislocations were simply electrically inert to a light-emitting process. Nevertheless, Rosner *et al.*[4] have shown in their cathodoluminescence study that dislocations influence carrier recombination and, most likely, act as nonradiative recombination centers in GaN. It was also demonstrated that negative charges exist near the edge dislocations, displaying acceptorlike behavior.[5] All of these arguments were recently supported by the models developed by Look and Sizelove,[6] Wright and Grossner,[7] and Elsner *et al.*[8] Their works showed that the threading edge dislocations in GaN are indeed electrically active, affecting not only the minority carrier transport parameters but also the luminescence efficiency. In this letter, we provide a different means of examining the physical properties of GaN film by observing for the first time the long-term photocapacitance decay behavior in undoped GaN. Our results show that the steady state value of the transient photocapacitance decays logarithmically in time defined by the time interval between light off and the commencement of measurement at room temperature. This dynamic response is inferred to be correlated closely to the electron-hole recombination at dislocations.

2. Experiments

The sample employed in this study is undoped GaN grown on a (0001) sapphire substrate using the low-pressure metalorganic vapor phase epitaxy (MOVPE) growth technique. The corresponding Hall concentration and mobility are 4.7×10^{16} cm^{-3} and 77 cm^2/V·s, respectively. During the experiment, metal Ni dots of 1 mm diameter were first deposited on the film as Schottky contacts through a metal mask by electron-gun evaporation. The ohmic contact was subsequently formed on the epilayer surface by depositing strips of Al, which exhibited good linear I–V characteristic and was suitable for our photocapacitance measurements.

For the measurements of photocapacitance, the Schottky diode was illuminated by a nominal 60 W tungsten lamp for 5 min at zero bias voltage. The sample was then used for the measurement of transient behavior at room temperature using a HP4194 impedance analyzer at different dark waiting times from 1 min to 12 h. For each measurement, a reverse bias of -1 V square voltage with duration of ~ 1.5 s was applied for the purpose of emptying the carrier in the depletion region. Pulses with a test frequency of 10 kHz and 100 meV oscillation level were employed to record the small signal diode capacitance. The trigger duration used was sufficiently long to attain the respective steady state capacitance value, $C_S(t)$, so that long-term photocapacitance behavior could be obtained. Attention was paid to ensure that the time interval between the consecutive measurements was at least 1 min. Under these circumstances, any possible intervention between the measurements can be minimized to a negligible extent.

3. Results and Discussions

Figures 1(a) and 1(b) show the transient capacitance of the undoped GaN measured at room temperature probed at different waiting times, t, after the illumination was switched off. As can be seen in Figs. 1(a) and 1(b), for each measurement when a square triggering voltage is applied, the capacitance signal increases exponentially at the beginning and saturates to a steady-state value within a duration of ~ 0.2 s. The uprising portion has been attributed primarily to the point defects associated with the 0.60 eV level below the conduction band as they exhibit the characteristics of the same time constant and defect concentration, as revealed by deep level transient spectroscopy measurements.[9] This particular trap, due to its fast dynamic response in nature, cannot be considered responsible for the long-term photocapacitance behavior. It is worth noting that the steady-state capacitances $C_S(t)$ in Figs. 1(a) and 1(b) were recorded respectively in 5 min and 1 h units and also plotted in shifted ordinates. The heights of $C_S(t)$

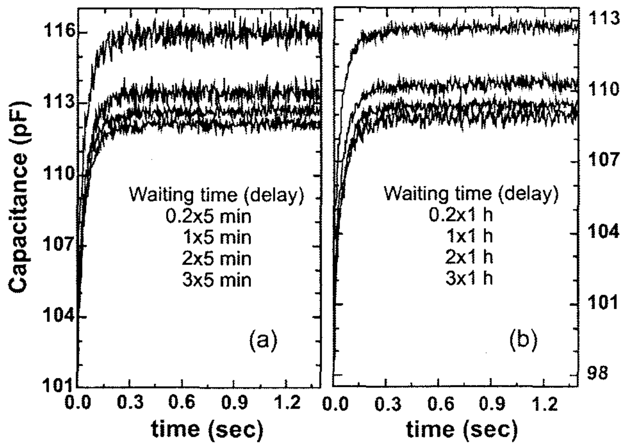

Fig. 1. The transient capacitance response of the undoped GaN during the applications of square voltage recorded at different waiting time, t, at room temperature.

on both sides of the figures, due to their logarithmic nature, are virtually the same for all different time scales used. That is, the heights of $C_S(t)$ are the same for $t = 0.2 \times 5\,\text{min}$, $t = 0.2 \times 1\,\text{h}$, and so forth.

Figure 2 depicts the plot of steady-state values of the photocapacitance, $C_S(t)$, versus t. $C_S(t)$ is found to decrease logarithmically as a function of t with its value dropping from 113 pF at $t = 5\,\text{min}$ to 107 pF at $t = 12\,\text{h}$. The change in $C_S(t)$ can be expressed approximately as:

$$\Delta C_S(t) \propto -\log(t). \tag{3.1}$$

Similar phenomenon in photoconductivity behavior was observed in the plastically deformed n-type GaAs reported by Nakata and Ninomiya.[10] They ascribe this unique feature to the carrier recombination involved with the dislocations presented in the epilayer. We believe this is also the very case which occurred in our heteroepitaxial GaN film.

It is known that due to the lack of a lattice-matched substrate, the GaN epitaxial film usually contains large quantities ($>10^8\,\text{cm}^{-2}$) of threading edge dislocations.[3] By using scanning capacitance microscopy, Hansen *et al.*[5] found that in the vicinity of dislocations, the electronic structure appears to be negatively charged, which is very different from the rest of the region. They attributed this to the presence of deep acceptor-like trap states near the valence band associated with threading dislocations. This view was soon supported by Wright and Grossner[7] and Elsner *et al.*[8] using density-functional theory to study the effects of doping and growth stoichometry on the core structure of threading dislocations for GaN. Their calculations showed that the edge dislocations indeed play an essential role as electron traps, i.e., acceptor-like defects, in an n-type GaN material. The foregoing arguments certainly provided us with valuable hints towards the explanation of our observed data.

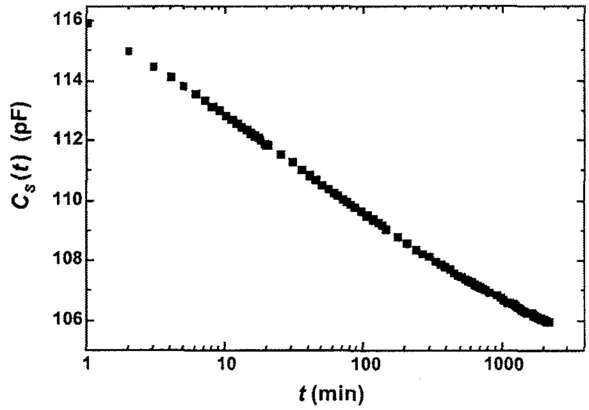

Fig. 2. The steady state value of transient capacitance, $C_S(t)$ versus waiting time t at room temperature.

In this experiment, the GaN sample was subjected to light illumination at the beginning, generating a substantial number of excess holes in the valence band as shown in Fig. 3(a). Owing to the characteristic of the short minority carrier lifetime (~6.5 ns) in n-GaN,[11] the excited holes soon migrate to the dislocations. At the end of photopumping, most traps along the dislocation lines are conceivably filled with holes and become neutrally charged [Fig. 3(b)]. When the light is switched off, the trapped holes remain at the dislocations until recombination with electrons from the conduction band [Fig.

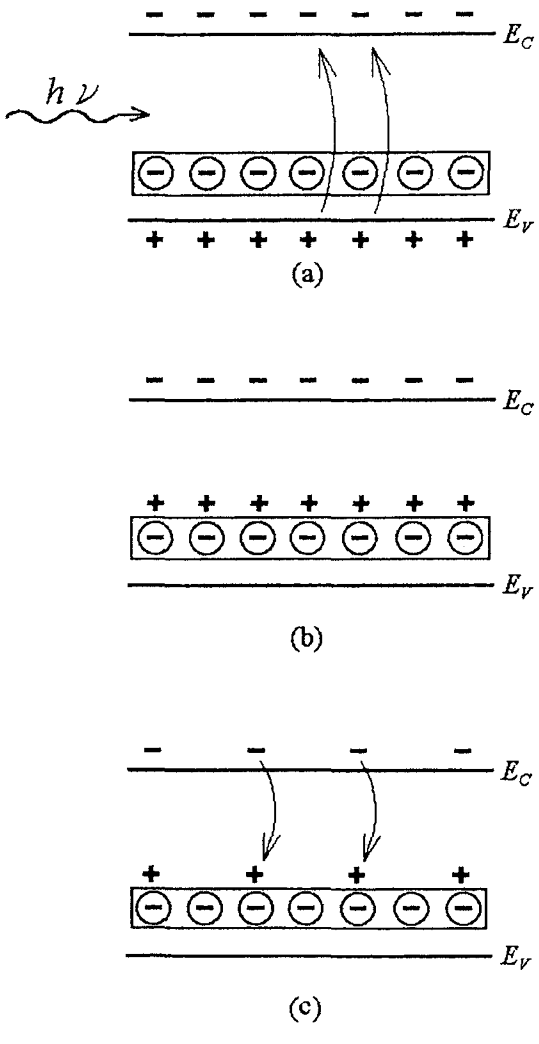

Fig. 3. The status of excess carriers in GaN (a) during the photopumping (b) at the time soon after the photopumping, and (c) at prolonged time after the switch-off of the light. The open rectangles enclosing negative charged ions symbolizes the groups of linear arranged dislocation traps.

3(c)]. It is worth mentioning that the capture of electrons by dislocations discussed here proceeds relatively slowly compared to the capture of holes in the valance band. This is because these dislocation traps in principle act as repulsive Coulomb scattering centers for nearby electrons. Unlike the filling of holes, a cylindrical potential barrier[6)] is presented between the free electrons and dislocation lines due to the nature of the negative charge property of the core dislocation.

The description of the electron captured by dislocations using the barrier-limited recombination model was given by Figielski.[12)] In this model, the electron capture rate for linearly arranged traps, such as dislocation lines, is assumed to be limited by the barrier height of the corresponding cylindrical potential, set up by the electrons already caught by the dislocations. The electrostatic potential at time t established in the depletion region due to the uniform trap concentration can be written as $\phi(t) = \phi_0 n_{\mathrm{T}}(t)/n_{\mathrm{T0}}$, where $n_{\mathrm{T}}(t)$ is the concentration of traps actually occupied with electrons and the subscript "0" denotes their final steady state values under the experimental condition. The height of the barrier increases gradually with the increasing number of trapped electrons, making the subsequent capture of electrons in the conduction band more difficult. Consequently, a prolonged charge transfer phenomenon resulted in the diode.

Since only those free electrons having sufficient energy to surmount the potential barrier can reach the trap site and recombine with holes, the rate equation for this electron capture process, therefore, can be written as:

$$\frac{dn_{\mathrm{T}}}{dt} = \sigma_{\mathrm{T}} v_n (N_{\mathrm{T}} - n_{\mathrm{T}})\, n \exp\frac{-q\phi(t)}{kT}, \tag{3.2}$$

where v_n is the thermal velocity of the electrons, σ_{T} and N_{T} are respectively the electron capture cross section and the total concentration of the dislocation traps, n represents the free electron concentration outside the barrier, and $n\exp[-q\phi(t)/kT]$ here is the amount of free electrons that can leap over the barrier. For simplicity, the concentration of the dislocation traps N_{T} is assumed to distribute uniformly throughout the semiconductor. With the initial condition $n_{\mathrm{T}}(0) = 0$ and the assumption of a slow electron filling process associated with the dislocation traps, i.e., $n_{\mathrm{T}}(t) \ll N_{\mathrm{T}}$, one can arrive at an approximate solution to eq. (3.2) in the form of:

$$n_{\mathrm{T}}(t) = \frac{kT}{q}\frac{n_{\mathrm{T0}}}{\phi_0}\ln\frac{t+t_0}{t_0}, \tag{3.3}$$

where

$$t_0 = \frac{kT}{q}\frac{n_{\mathrm{T0}}}{\sigma_{\mathrm{T}} v_n n \phi_0 N_{\mathrm{T}}}. \tag{3.4}$$

For $t \gg t_0$ and after substituting eq. (3.4), eq. (3.3) can be expressed as a linear equation in a linear form of:

$$n_{\mathrm{T}}(t) = a + b\ln t, \tag{3.5}$$

where $a = -\sigma_{\mathrm{T}} v_n n N_{\mathrm{T}} t_0 \ln t_0$ and $b = \sigma_{\mathrm{T}} v_n n N_{\mathrm{T}} t_0$. We propose the photocapacitance $C_{\mathrm{S}}(t)$ is related to the charge state affiliated with the dislocation traps and can be expressed as:[13)]

$$\begin{aligned} C_{\mathrm{S}}(t) &= C_{\mathrm{S}}(0)[1 - n_{\mathrm{T}}(t)/N_{\mathrm{D}}]^{0.5} \\ &\approx C_{\mathrm{S}}(0)[1 - 0.5 n_{\mathrm{T}}(t)/N_{\mathrm{D}}] \end{aligned} \tag{3.6}$$

for $n_{\mathrm{T}}(t) \ll N_{\mathrm{D}}$, where N_{D} is the donor density in the space charge region. Hence from eq. (3.6) and the $C_{\mathrm{S}}(t)$ versus t curve in Fig. 2, we then obtained $n_{\mathrm{T}}(t)$ of each t and plotted it in Fig. 4. From the ratio of the retrieved slope and intercept of $n_{\mathrm{T}}(t) = a + b\ln t$, we obtained the time constant t_0 of ~34.5 s. Since we know that $N_{\mathrm{T}}/N_{\mathrm{D}}$ has a lower limit of ~20% from Fig. 4, together with the obtained time constant t_0, slope b, and $n = 4.7 \times 10^{16}\,\mathrm{cm}^{-3}$, we obtained an upper limit of capture cross section of $\sigma_{\mathrm{T}} \approx 2.89 \times 10^{-27}\,\mathrm{cm}^2$. For comparison, a straight line using the same time constant and the same upper limit value of the capture cross section is also plotted in Fig. 4 to simulate the conditions of $t \gg t_0$.

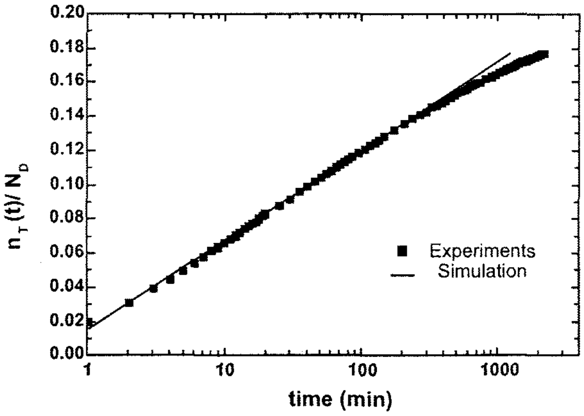

Fig. 4. The ratio of $n_{\mathrm{T}}(t)$ and N_{D} versus waiting time t at room temperature.

From Fig. 2 and Fig. 4, it is evident that our measured photocapacitance and trap concentration essentially follow the theoretical prediction when the waiting time t (delay) is longer than 3 min, satisfying the condition of $t \gg t_0$. The capture cross section σ_{T} obtained is much smaller than the physical size of a hydrogen atom ($\sim 10^{-15}\,\mathrm{cm}^2$). This is consistent with our earlier repulsive Coulomb potential assumption. Nonetheless, departure of the experimental data from the simulated line is observed for $t > 500$ min. After such a long waiting time t, the trapped electron concentration $n_{\mathrm{T}}(t)$ tends to approach its final saturation value n_{T0}. Under this circumstance, the linear dependence of cylindrical potential on the concentration of the trapped electron is no longer valid and the electron capture process slows down markedly and eventually ceases.

In summary, the dynamic photocapacitance decay behavior of an undoped, MOVPE-grown GaN film observed at various waiting times t after switching off illumination was measured. The steady-state value of the capacitance decays logarithmically with the waiting time t. We argue that this phenomenon is closely related to the electron capture process at the dislocation traps, which can be explained satisfactorily with the barrier-limited recombination model. The characteristic time constant t_0 and the capture cross section σ_{T} of the electron filling process were experimentally determined to be ~34.5 s and $<2.89 \times 10^{-27}\,\mathrm{cm}^2$, respectively.

Acknowledgements

The authors are grateful for the support by the National Science Council of the Republic of China under Contract Nos. NSC89-2112-M009-061, NSC89-2112-E009-058, and NSC89-2112-M009-056.

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