6-1-1996

Thermally Stimulated Current Trap in GaN

David C. Look

Wright State University - Main Campus, david.look@wright.edu

Z-Q. Fang

W. Kim

Ö. Aktas

A. Botchkarev

See next page for additional authors

Follow this and additional works at: <https://corescholar.libraries.wright.edu/physics>

Part of the [Physics Commons](#)

Repository Citation

Look, D. C., Fang, Z., Kim, W., Aktas, Ö., Botchkarev, A., Salvador, A., & Morkoç, H. (1996). Thermally Stimulated Current Trap in GaN. *Applied Physics Letters*, 68 (26), 3775-3777.
<https://corescholar.libraries.wright.edu/physics/56>

This Article is brought to you for free and open access by the Physics at CORE Scholar. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of CORE Scholar. For more information, please contact library-corescholar@wright.edu.

Authors

David C. Look, Z-Q. Fang, W. Kim, Ö. Aktas, A. Botchkarev, A. Salvador, and H. Morkoç

Thermally stimulated current trap in GaN

D. C. Look and Z.-Q. Fang

University Research Center, Wright State University, Dayton, Ohio 45435

W. Kim, Ö. Aktas, A. Botchkarev, A. Salvador, and H. Morkoç^{a)}

Materials Research Laboratory and Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 26 February 1996; accepted for publication 22 April 1996)

A thermally stimulated current peak, occurring at 100 K for a heating rate of 0.4 K/s, has been found in semi-insulating GaN grown by molecular beam epitaxy. This peak has contributions from two traps, with the main trap described by the following parameters: emission thermal activation energy $E \approx 90 \pm 2$ meV, effective capture cross-section $\sigma \approx 3 \pm 1 \times 10^{-22}$ cm², and $N\mu\tau \approx 3 \pm 1 \times 10^{14}$ cm⁻¹ V⁻¹, where N is the trap concentration, μ the mobility, and τ the free-carrier lifetime. This trap is much deeper than the typical shallow donors in conducting GaN, but shallower than any of the centers reported in recent deep level transient spectroscopy measurements. © 1996 American Institute of Physics. [S0003-6951(96)02826-4]

GaN and its related ternaries, AlGaN and InGaN, are being widely developed for blue/uv optical emitters and detectors, and high-temperature electronics.¹ Very recently a blue diode laser composed of these materials has been reported.² For both optical and electronic devices, deep centers can be very important, and thus must be understood. Capacitance-based deep level transient spectroscopy (DLTS) has been applied in a few cases,³⁻⁶ but this technique is useful only for conductive samples. Recently, high-resistivity, or semi-insulating (SI) GaN has been reported,⁷⁻⁹ but little is known about the deep centers in this material. A useful characterization technique for high-resistivity samples is thermally stimulated current (TSC) spectroscopy; e.g., TSC has been applied extensively to SI GaAs.¹⁰⁻¹² In this work, we use TSC to study SI GaN grown by molecular beam epitaxy (MBE). Although no other TSC work in GaN has been published at this time, to our knowledge, an abstract on the subject has recently appeared¹³ and should be published soon.

Thermally stimulated current involves the low-temperature filling of electron traps (above the Fermi-level E_F), or hole traps (below E_F), and then the thermal emptying of these traps by slowly raising the temperature.¹⁰ With a bias on the sample, the latter process will produce a current, which is recorded. Typically, the traps are filled at about 80 K (or below) by several minutes of illumination with above-band gap light, then emptied (in the dark) by sweeping temperatures at rates $\beta \approx 0.05$ –0.5 K/s. The emission is thermally activated, so the emission rate e_n (for electrons) is given by the usual formula determined from detailed-balance considerations

$$e_n = \frac{g_0}{g_1} N'_C T^{3/2} \sigma_n v_n e^{-E/kT}, \quad (1)$$

where g_0/g_1 is a degeneracy factor, $N'_C T^{3/2}$ is the effective conduction-band density of states, σ_n is the electron capture

cross section for the trap, $v_n = \sqrt{8kT/\pi m_n^*}$ is the thermal velocity, and E is the trap energy with respect to the conduction band. A similar formula can be written for hole emission. A given trap will begin to emit at a characteristic temperature, with the emission rate increasing rapidly according to Eq. (1). However, the emission probability will drop as the trap is depleted of electrons (or holes), so that the current I_{TSC} will go through a peak. It is straightforward to show that¹⁰

$$I_{TSC} = e \mu_n \tau_n V \frac{wd}{l} N e_n \exp\left(-\int_{T_0}^T \frac{e_n}{\beta} dT'\right), \quad (2)$$

where e is the electronic charge, μ_n the electron mobility, τ_n the free-electron lifetime, V the bias voltage, w , d , and l the sample width, thickness, and length, respectively, n the trap concentration, T_0 the trap filling temperature, and β the heating rate. Here, it is assumed that all of the N traps are filled during the illumination. It should be noted that the quantities μ_n , τ_n , σ_n , and E may also be temperature dependent. In fact, σ_n and E are often written as $\sigma_n = \sigma_{n0} \exp(-E_\sigma/kT)$ and $E = E_0 - \alpha T$. Then it is seen, by inserting these quantities into Eqs. (1) and (2), that the measured activation energy is really $E_0 + E_\sigma$ and the measured σ_n is really $(g_0/g_1) \sigma_{n0} \exp(\alpha/k)$; the latter quantity is sometimes called σ_{na} , the “apparent” capture cross section. Thus, a fit of Eq. (2) to a TSC spectrum of a given trap will yield the following fitting parameters: $\mu_n \tau_n N$, σ_{na} , and $(E_0 + E_\sigma)$. It is impossible to further separate any of these parameters without independent knowledge.

The sample was a 6- μ m-thick GaN layer grown at 800 °C on *c*-plane sapphire by using ammonia as the nitrogen source. The 296 K resistivity was about 10^6 Ω cm, but the mobility could not be determined because no Hall effect could be measured. Photoluminescence measurements at 2 K showed sharp (~ 5 meV) emission lines at 3.4831 eV (A exciton) and 3.4896 eV (B exciton), and reflection measurements showed all three free excitons, A, B, and C. Thus, the layer was of high quality.

The TSC spectrum, for a heating rate $\beta = 0.2$ K/s, is shown in Fig. 1. A clear peak occurs at about 100 K, and then a shoulder at about 130 K. At higher temperatures, the

^{a)}On sabbatical leave at Wright Laboratory, Wright-Patterson Air Force Base, OH, 45435 under a University Resident Research Program funded by the Air Force Office of Scientific Research.

FIG. 1. Thermally stimulated current I_{TSC} vs T for sample 5069. The heating rate was 0.2 K/s.

current continues to increase, evidently due to a persistent photocurrent, I_{PPC} . The dark current, I_{dark} , is only about 0.2 nA at 300 K, so $I_{dark} \ll I_{PPC}$ over the range of this plot. If the sample is heated to 400 K for a few minutes, and then cooled to 80 K in the dark, I_{PPC} disappears. The reason for the metastable nature of the photocurrent is not known yet, but such a phenomenon has been seen in many semiconductors, including GaAs. The PPC may hide smaller traps in the region $T > 150$ K.

In this work, we will consider only the peak at 100 K, which is replotted on a different temperature scale in Fig. 2. A common approximation in TSC analysis is to assume $E \approx kT_m \ln(T_m^4/\beta)$, where T_m is the temperature at the peak, 100 K in this case.¹⁰ This approximation gives $E \approx 0.17$ eV. However, we have more accurately analyzed the data with a least-squares fit to Eq. (2). The first fitting attempt, which assumed a single trap, failed. [This failure was unexpected, because we get excellent single-trap fits of Eq. (2) to most of the TSC peaks in SI GaAs (see Ref. 14).] A two-trap analysis, i.e., $I_{TSC} = I_{TSC-A} + I_{TSC-B}$, gives a good fit to the peak, although there is clearly additional current beyond these two

FIG. 2. A theoretical fit (dashed line) of the low-temperature portion of the TSC spectrum presented in Fig. 1. The independent contributions from traps A and B are also shown.

peaks. A fit (not shown) for a different heating rate, $\beta = 0.4$ K/s, gives nearly the same fitting parameters for trap A, but not for trap B. Thus, we are confident of the fitting parameters only for trap A at this time: $E \approx 90 \pm 2$ meV, $\sigma_{na} \approx 3 \pm 1 \times 10^{-22}$ cm², and $N\mu_n\tau_n \approx 3 \pm 1 \times 10^{14}$ cm⁻¹ V⁻¹. Here, we have assumed that μ_n and τ_n do not change significantly in the temperature range of this fit. Note that the accurately fitted value of E , 90 meV, is much different than the estimated value, 170 meV. Note also that the full line shape analysis [Eq. (2)] was necessary in order to see that the experimental peak contained contributions from more than one trap.

The value of the parameter $N\mu_n\tau_n$ is reasonable; e.g., if we assume $\mu_n \approx 10^3$ cm²/V s and $\tau_n \approx 10^{-6}$ s, at 100 K, then $N \approx 10^{17}$ cm⁻³. The value of the apparent cross section, on the other hand, is lower than expected. If we estimate $E_\sigma \approx \alpha \approx 0$, and $g_0/g_1 \approx 1$, then $\sigma_n \approx 10^{-22}$ cm², a value which suggests a strong repulsive barrier to capture. However, further investigation will be necessary before these parameters can be fully understood.

For completeness, we also give the fitting parameters for trap B: $E \approx 170 \pm 50$ meV, $\sigma_{na} \approx 10^{-16} - 10^{-21}$ cm², and $N\mu_n\tau_n \approx 2.5 \pm 0.5 \times 10^{14}$ cm⁻¹ V⁻¹. The inaccuracy of E and σ_{na} for trap B are due to differences in the fitting parameters for data taken at different heating rates. Thus, we are not as confident of the trap B parameters as we are of those for trap A.

Other groups have used DLTS on conductive samples to find the following activation energies: 0.26, 0.58, and 0.66 eV, in GaN grown by hydride vapor-phase epitaxy on GaN and ZnO buffer layers (substrate not by hydride vapor-phase epitaxy on GaN and ZnO buffer layers (substrate not mentioned)),³ 0.18 and 0.49 eV in metalorganic chemical vapor deposition (MOCVD) GaN grown on AlN buffer layers,⁴ and 0.14, 0.49, and 1.63 eV in MOCVD GaN grown on GaN buffer layers.⁶ In the latter two cases, the substrate was (0001) sapphire. In another study, involving photoemission capacitance spectroscopy, levels at 0.87, 0.97, 1.25, and 1.45 eV were found.⁵ All of these energies are higher than that found for trap A in the present study.

Although we have no way to clearly identify our 90 meV center at this time, we may note that it occurs in a sample which is expected to be nitrogen rich. Thus, it is possibly associated with one of the defects expected to be dominant under N-rich conditions, i.e., a Ga vacancy, N interstitial, or N antisite. Theoretical calculations predict Ga vacancy levels close to the valence band, and N antisite levels close to the conduction band; thus, the former may act as a hole trap and the latter, an electron trap.¹⁵ (If our center is a hole trap, rather than an electron trap, then the fitted cross-section σ would have a different value, due to the different density of state and thermal velocity for holes.) An electron attempting to trap on the N antisite would evidently face a strong electron-electron repulsion, which might explain the low capture cross section observed. However, all of these speculations must await further confirmation.

We wish to thank R. Heil for manuscript preparation. D. C. L. and Z. Q. F. were supported under U.S. Air Force Contract No. F33615-95-C-1619. The work at the University

of Illinois was funded by grants from ONR, AFOSR, and BMDO, and was monitored by M. Yoder, Y. S. Park, K. Wu, and J. Johnson.

- ¹S. Strite and H. Morkoç, J. Vac. Sci. Technol. B **10**, 1237 (1992); S. N. Mohammad and H. Morkoç, Prog. Quantum Electron. (in press).
- ²S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Jpn. J. Appl. Phys. **35**, L74 (1996).
- ³P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo, and K. Miyake, J. Appl. Phys. **76**, 304 (1994).
- ⁴W. Gotz, N. M. Johnson, H. Amano, and I. Akasaki, Appl. Phys. Lett. **65**, 463 (1994).
- ⁵W. Gotz, N. M. Johnson, R. A. Street, H. Amano, and I. Akasaki, Appl. Phys. Lett. **66**, 1340 (1995).
- ⁶W. I. Lee, T. C. Huang, J. D. Guo, and M. S. Feng, Appl. Phys. Lett. **67**, 1721 (1995).
- ⁷R. J. Molnar, T. Lei, and T. D. Moustakas, Appl. Phys. Lett. **62**, 72 (1993).
- ⁸C. Wang and R. F. Davis, Appl. Phys. Lett. **63**, 990 (1993).
- ⁹D. K. Gaskill, A. E. Wickenden, K. Doverspike, B. Tadayon, and L. B. Rowland, J. Electron. Mater. **24**, 1525 (1995).
- ¹⁰D. C. Look, Semicond. Semimet. **19**, 75 (1983).
- ¹¹D. I. Desnica, J. Electron. Mater. **21**, 463 (1992).
- ¹²Z.-Q. Fang and D. C. Look, J. Appl. Phys. **69**, 8177 (1991).
- ¹³Z. C. Huang, J. C. Chen, and B. D. Mott, Mater. Res. Soc. Symp. Proc. **395** (to be published).
- ¹⁴Z.-Q. Fang and D. C. Look (unpublished).
- ¹⁵P. Boguslawski, E. L. Briggs, and J. Bernholc, Phys. Rev. B **51**, 17255 (1995).