Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **AUG 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Observation of deep traps responsible for current collapse in GaN metal-semiconductor field-effect transistors**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPLIED PHYSICS LETTERS VOLUME 75, NUMBER 25 20 DECEMBER 1999

Observation of deep traps responsible for current collapse in GaN metal–semiconductor field-effect transistors

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(Received 3 August 1999; accepted for publication 28 October 1999)

Deep traps responsible for current collapse phenomena in GaN metal–semiconductor field-effect transistors have been detected using a spectroscopic technique that employs the optical reversibility of current collapse to determine the photoionization spectra of the traps involved. In the *n*-channel device investigated, the two electron traps observed were found to be very deep and strongly coupled to the lattice. Photoionization thresholds for these traps were determined at 1.8 and at 2.85 eV. Both also appear to be the same traps recently associated with persistent photoconductivity effects in GaN. © *1999 American Institute of Physics.* [S0003-6951(99)04351-X]

III–V nitrides are presently of great interest because of the potential for developing from this material system a wide range of optoelectronic devices operating in the blue and ultraviolet portions of the spectrum, as well as electronic devices capable of operating at high frequency, high temperature, and high power. Significant advances have been made in both of these areas, with the commercialization of nitride-based light-emitting diodes (LEDs) and lasers, and with the fabrication of nitride-based field-effect transistors (FETs) with continuous-wave output powers up to 6.9 W/mm (Ref. 1) and high-frequency operation up to $f_T = 67\,\mathrm{GHz}$ and $f_{\max} = 140\,\mathrm{GHz}$.[2] However, such levels are not always reproducible because of device limitations resulting from the presence of trapping centers in the material. As a result, a great deal of interest has been generated in detecting and identifying these defects and in determining in which part of the device structure they are located.

Current collapse (CC) is a trap-related phenomenon that severely limits the output power of FETs, and has been observed in Si metal–oxide–semiconductor FETs,[3] $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ modulation-doped FETs (Ref. 4) (MODFETs), and recently, in nitride-based $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N/GaN}$ heterostructure insulated gate FETs (Ref. 5) (HIGFETs), and in GaN metal–semiconductor field-effect transistors (MESFETs).[6] The effect results from the trapping of hot carriers by deep centers located in regions of the device structure outside of the conducting channel. The excess charge associated with the trapped carriers produces a depletion region in the conducting channel, which results in a partial pinch-off of the device and a severe degradation of the drain current characteristics. The effect can be reversed by liberating trapped carriers either thermally by emission at elevated temperatures or optically by photoionization. In the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N/GaN}$ heterostructures it was suggested, by analogy with work done in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ MODFETs, that the traps responsible were located in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ barrier layer.[5] In the GaN MESFETs, it was assumed that the high-resistivity (HR) GaN insulating layer was the source of the trapping centers.[6]

There have been several studies of the effect of light on CC. For example, Kastalsky and Kiehl[4] measured the spectral dependence of the conductance in an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunction test structure, and concluded that the collapse resulted from processes in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer. Khan *et al.*[5] observed increases in the drain current of an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N/GaN}$ HIGFET near 360 nm, corresponding to the AlGaN band edge, and near 650 nm, which was associated with an unidentified deep trap. Similarly in GaN MESFETs, Binari *et al.*[6] observed an optically induced restoration of the drain current that decreased dramatically in effectiveness with increasing wavelength.

In this work, we report a method to extract the signatures of specific trap levels that are responsible for current collapse in FET structures. The method is based upon the fact that since light can photoionize the trapped carriers that are responsible for CC, the spectral dependence of this effect should reflect the photoionization spectrum of the trap. The photoionization spectrum is a unique characteristic of a defect, and can be used to identify or to ''tag'' a particular trapping center. Although this technique is equally applicable to heterostructures, we will concentrate in this letter on the GaN MESFET, which consists of a thin *n*-GaN channel layer on top of a HR GaN insulating layer. After the application of a high source–drain bias, hot carriers are trapped at deep centers which, because of the simplicity of the structure, can be assumed to reside in the semi-insulating HR layer. The experiment itself is carried out by the following sequence of events: First, the device is initialized with a GaN LED, as described below. Then, the source–drain voltage V_D is scanned up to high voltage (35 V). This fills the traps, and the fully collapsed $I-V$ curve is then measured in the dark. This procedure is repeated again, with the measurement carried out with illumination by light of wavelength λ for duration t. The drain current I_D for each measurement (light off, light on) is then extracted from the data at a chosen, fixed drain voltage V_0 for both measurements. The difference between these represents the increase in drain current at V_0 above the fully collapsed (dark) $I-V$ curve due to the light illumination, as shown in Fig. 1 for illumination at 470 nm. This increase reflects the number of carriers that have been optically ejected from the traps. By normalizing the frac-

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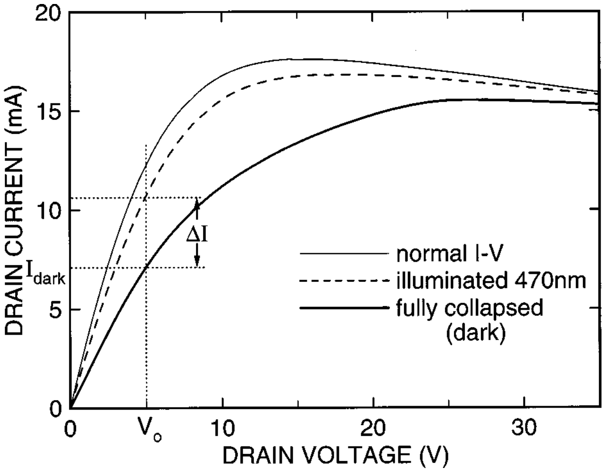

FIG. 1. $I-V$ characteristics of a GaN MESFET, where the fully collapsed curve measured in the dark (bold line) and the curve obtained under optical illumination (dashed curve) were both measured after the device was scanned up to high voltage.

tional increase in drain current (relative to that in the dark) by the total number of incident photons at each wavelength, we arrive at an experimentally measured response function

$$S(\lambda)\equiv\frac{1}{\Phi(\lambda)t}\,\frac{\Delta I(\lambda)}{I_{\mathrm{dark}}}, \tag{1}$$

where $\Phi(\lambda)$ is the incident photon flux, and $\Delta I(\lambda)$ and I_{dark} are the light-induced drain current increase and the fully collapsed (dark) drain current, respectively, both measured at V_0. The product $\Phi(\lambda)t$ is just the total number of photons/cm^2 incident on the device during illumination.

The net effect of the light illumination on the device is to reduce the total amount of trapped charge, leading to a decrease in both the width of the depletion region and the built-in potential across the *n*-channel-HR layer interface. In a future publication it will be shown[7] that the response function $S(\lambda)$ is proportional to the photoionization cross section of the trap under the following conditions: (1) the drain voltage V_0 at which the current is measured is small enough to still be approximately in the linear regime, and (2) the product $\sigma(\lambda)\Phi(\lambda)t \ll 1$, where $\sigma(\lambda)$ is the photoionization cross section of the trap.

For reproducible measurements of CC, it was found necessary to initialize the device before each measurement by proximity illumination with a blue GaN LED (1 mW), which emptied all or most of the traps. If a charge distribution was already present at the channel/HR interface, the photoexcitation of those nonequilibrium trapped carriers enabled their return to the channel under the influence of the built-in field, thus initializing the device to the equilibrium condition.

Details of the MESFET design and characterization are described in Ref. 6. The FET was fabricated with a source–drain spacing of 5 μm, a gate width of 150 μm, and a gate length of 1.5 μm. The 200-nm-thick *n*-GaN active channel layer was grown on top of a 3-μm-thick, undoped semi-insulating GaN buffer layer. Hall measurements at 300 K indicated a channel carrier concentration of $2\times10^{17}\,\mathrm{cm}^{-3}$ and a mobility of 410 cm^2/V s. $I-V$ characteristics were determined using an HP4145B semiconductor parameter analyzer, which measures the drain characteristics with a single sweep of V_D for each gate bias. The measurements were all carried out at zero gate bias. At higher drain voltages ($V_D > 15\,\mathrm{V}$) the decrease in drain current (see Fig. 1) is due to heating effects. Monochromatic light was provided by a 75 W Xe arc or a tungsten–halogen lamp, and a Spex 1680B 0.22 m double monochromator with a 3.5 nm bandpass, resulting in power densities of a few μW/cm^2.

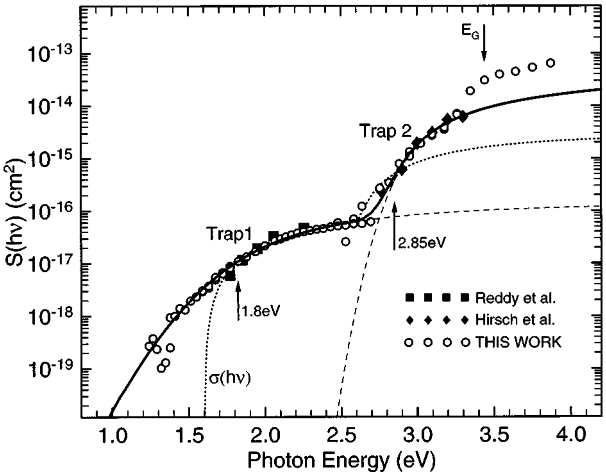

FIG. 2. Spectral dependence of the current collapse response function $S(h\nu)$. The open circles are the experimental data, and the solid symbols represent recent (scaled) PPC data. The dotted line is an unsuccessful fit of the data to a standard deep-level photoionization cross section $\sigma(h\nu)$, while the heavy solid line is a fit of the data following the approach in Ref. 12, which is essentially a convolution of the photoionization cross section with a Gaussian broadening function.

The results of these measurements, reflected in the response function $S(h\nu)$ as a function of incident photon energy $h\nu$ are shown as the open circles in Fig. 2. It is clear that there are two broad absorptions associated with photoionization from two distinct traps, which we have labeled traps 1 and 2. From the photon energies involved, it appears that these are both very deep traps. There is also a rise in the drain current near the GaN band gap, which is probably due to the injection of photoexcited carriers into the channel. The results of two recent spectral studies of persistent photoconductivity (PPC) in GaN by Reddy *et al.*[8] and by Hirsch *et al.*[9] are shown (scaled in magnitude) in Fig. 2 to exhibit very similar spectral dependences to those of traps 1 and 2, respectively. This suggests that the traps responsible for the PPC reported in these studies may be the same as those responsible for CC in the present work.

The spectral dependence of the photoionization cross section of a deep level may take one of several analytical forms.[10] However, none of these were found to successfully fit the data in Fig. 2. An example is shown as the dotted curve in Fig. 2, which represents a best fit using the relation $\sigma(h\nu)=A(h\nu-E_{\mathrm{th}})^{3/2}/(h\nu)^3$, where E_{th} is the photoionization threshold energy. These fail to fit the data because the absorptions are extremely broad. This breadth and the observed trap depths suggest that we are observing defects that are very strongly coupled to the lattice. In such cases, the photoionization cross section must be determined taking lattice relaxation into account. The result is essentially a convolution of the photoionization cross section and a Gaussian broadening function. This approach was necessary to fit photoionization data for the $EL2$ center in GaAs,[11] the DX

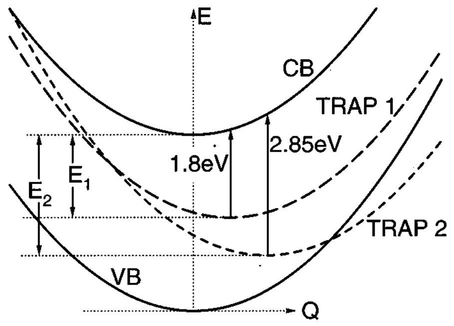

FIG. 3. Sketch of a configuration coordinate diagram showing the relationship of the deep traps and the band edge. E_1 and E_2 represent the thermal trap depths, while the optical transition energies indicate the photoionization thresholds determined in the present work.

center in AlGaAs,[12] and recently, the $E2$ defect in GaN.[13] Following Mooney *et al.*,[12] we obtain a very good fit of the present data, which is shown as the solid line in Fig. 2. The dashed lines represent the individual contributions from each trap. The fitted values of relative magnitude, threshold energy, and full width at half maximum are found to be $3\times10^{-17}\,\mathrm{cm}^2$, 1.8 eV, and 0.6 eV for trap 1, and $2.8\times10^{-15}\,\mathrm{cm}^2$, 2.85 eV, and 0.25 eV for trap 2. The fitted linewidths confirm that these are very broad absorptions. Consequently, the photoionization threshold energies do not necessarily coincide with any sharp absorption edges. A rough sketch of a configuration coordinate diagram is shown in Fig. 3 to indicate the relationship of the threshold energies and the band edges, and to emphasize that these are very deep levels. It should be noted that trap depths (indicated by E_1 and E_2 in Fig. 3) that might be determined by thermal measurements, such as deep-level transient spectroscopy, do not correspond to the trap photoionization thresholds: The two differ by the lattice relaxation energy, as shown in Fig. 3.

As the measurement technique is based upon the reversal of CC, it is specifically sensitive to the traps responsible for this phenomenon, but also limited to only those traps. However, the two traps observed here to cause CC appear to be related to PPC effects as well, as seen in Fig. 2. That a single trap should be associated with both effects is not new: the *DX* center[14] is a well-known example of such a defect. The CC process requires only that the dominant trapping center have a slow thermal emission rate and be present in significant numbers in the appropriate regions of a device structure. PPC due to deep traps, on the other hand, requires a slow capture rate, which can result from either a large capture barrier or a small capture cross section. (Hirsch *et al.*[9] have already concluded a very small capture cross section for the PPC center that appears to coincide with trap 2.) As these two requirements do not conflict, it is clear that under the right conditions it is possible for some (but not all) deep traps to bring about both PPC and CC.

In this work, we have demonstrated that the spectral dependence of the optical quenching of CC can be used to reveal the defects responsible for this effect. Two deep traps were observed in the HR GaN layer with photoionization thresholds at 1.8 and 2.85 eV. These were determined assuming that the centers were strongly coupled to the lattice, as suggested by their large linewidths and ionization energies. Both traps appear to be the same as those recently observed in PPC measurements.

The authors would like to thank R. Magno for some very helpful discussions and a critical reading of the manuscript. This work was supported in part by the Office of Naval Research.

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