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High field electron dynamics in dilute nitride Ga(AsN)

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We investigate the high electric field dynamics of conduction electrons in dilute nitride $GaAs_{1-x}N_x$ diodes. At low temperature ($T<40$ K), we show that the trapping of hot electrons at localized states leads to low frequency oscillations (<1 Hz) of the current at high bias. This slow dynamics is replaced at higher temperatures by a fast response of the current in the subterahertz frequency range, which we relate to the interaction of hot electrons with resonant nitrogen-related states in the conduction band. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2960547]

Dilute nitride semiconductors are a class of alloys in which a small amount of nitrogen (N) is incorporated in the lattice of III-V compounds such as GaAs.[1] The incorporation of isoelectronic N on the pnictide site (e.g., As) gives rise to a highly localized electronic state, whose energy level is resonant with the continuum of extended conduction band (CB) states of the host lattice. The interaction between these two types of states provides a means of tuning not only the energy bandgap, but also the effective mass and group velocity of conduction electrons.[1–5] Of particular interest is the emergence of a negative differential conductance (NDC) effect, caused by the formation of a fully developed energy gap in the CB of the host crystal.[6] This effect is qualitatively different from the mechanism responsible for NDC in transferred electron devices (Gunn diodes)[7,8] and semiconductor superlattices,[9] and has potential for terahertz device applications.[6]

In this letter, we study the high electric field dc and ac electron dynamics in the dilute nitride semiconductor $GaAs_{1-x}N_x$ ($x=0.1\%$). We show that at low temperature ($T<40$ K) and for dc electric fields larger than a critical value (~2 kV/cm), hot electrons are trapped onto localized states, thus leading to low frequency (<1 Hz) oscillations (LFOs) of the current; this slow dynamics is replaced at higher temperatures by a fast response of the current in the subterahertz frequency range. We investigate the ac dynamics by measuring harmonic generation of ac current and the changes in the dc conductivity in the presence of external terahertz radiation. The effects described in this letter are not only of fundamental interest, but also demonstrate that the mechanism leading to the NDC in $GaAs_{1-x}N_x$ can be a fast process relevant to terahertz electronics. This region of the electromagnetic spectrum, ranging from approximately 0.1 to 10 THz, is often referred to as the "terahertz gap" due to the need for compact, solid state devices that operate in this frequency range.[10]

We investigated a number of n^+-n-n^+ GaAs/$GaAs_{1-x}N_x$/GaAs heterostructures grown by molecular beam epitaxy on (100)-oriented Si-doped GaAs substrates. The growth sequence is as follows: a 0.2-μm-thick n^+ GaAs buffer layer (Si: 2×10^{18} cm^{-3}), an n-type $GaAs_{1-x}N_x$ layer ($x=0.1\%$) of thickness $t=0.6$ μm, doped with Si to 1×10^{17} cm^{-3}; the growth was completed with a 0.5-μm-thick n^+ GaAs cap layer (Si: 2×10^{18} cm^{-3}). All samples were processed into circular mesa diodes of diameter $d=20$ or 10 μm, with Ohmic contacts to the substrate and top capping layer. These structures have a low field electron mobility $\mu=0.2$ m^2/V s at $T=2$ K and 295 K.[11] This relatively low value of μ is fully consistent with that obtained from independent Hall measurements on modulation doped $GaAs_{1-x}N_x$ quantum well layers with $x=0.1\%$ ($\mu=0.20$ m^2/V s at $T=2$ K) (Ref. 12) and is due to strong elastic scattering by the randomly distributed and highly electronegative N atoms.[13]

Figure 1 shows the current-voltage $I(V)$ curves of one of our devices at different temperatures T. The $I(V)$ curves exhibit an Ohmic region at low bias, followed by a sublinear V dependence of the current or a region of NDC. We note that (i) at low T (4–30 K) and high bias, the current is almost independent of V over a wide range of applied biases, (ii) the low bias conductance for all the $I(V)$ curves is independent of temperature, indicating that the mobility and carrier con-

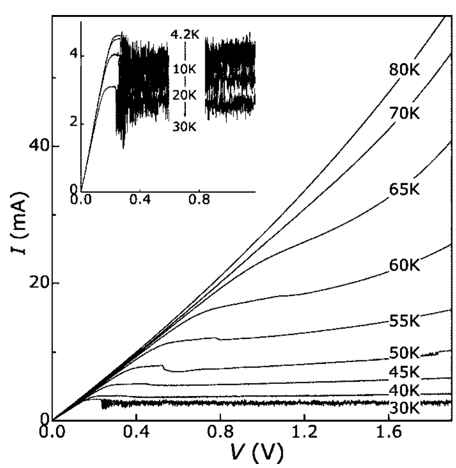

FIG. 1. $I(V)$ curves vs T for a 20 μm diameter mesa diode. The inset shows the $I(V)$ curves from $T=4.2$ to 30 K. For the $I(V)$ measurements at $T\leq30$ K, the diode was excited with 633 nm laser light and power density $P<50$ W m^{-2}.

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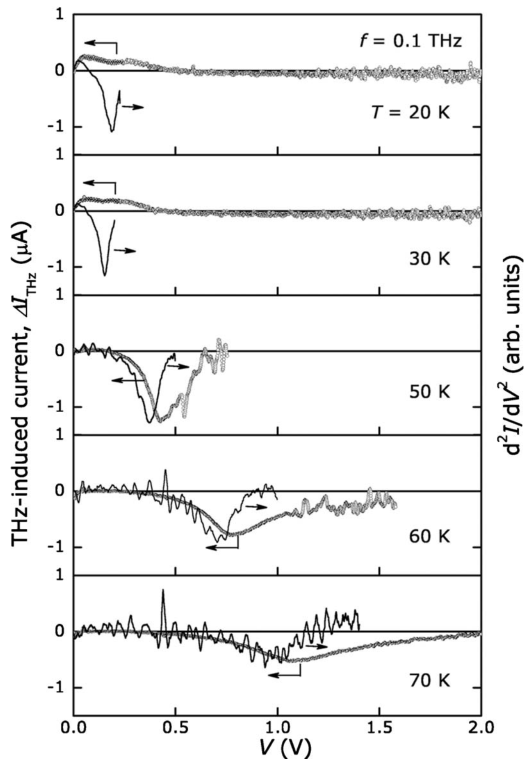

FIG. 2. (a) V dependence of ΔI_{THz} (circles) and of d^2I/dV^2 (solid curves) from $T=20$ to 70 K for a 20 μm diameter mesa diode. For these measurements, the diode was excited with radiation of frequency $f=0.1$ THz and power density of about 10^2 W m^{-2}.

centration are independent of T at low electric fields, (iii) there is a thermally activated increase of the high-bias current and of the critical bias V_T for NDC. The value of V_T increases by more than a factor of 5 for T in the range 30–80 K. This strong T dependence differs from that observed in other systems with NDC such as Gunn diodes[14] and superlattices[15] in which the temperature effects are much weaker.

The strong sensitivity on temperature of the photoconductivity response ΔI_{THz} of the diode when excited with terahertz electromagnetic radiation from a backward wave oscillator source is shown in Fig. 2. Here we plot the bias dependence of the average dc current ΔI_{THz} induced by radiation of frequency $f=0.1$ THz. Our data show that ΔI_{THz} is strongly affected by temperature: for $T<40$ K and small applied dc bias voltages ($V<0.4$ V), $\Delta I_{\mathrm{THz}}(V)$ is weak and positive. Increasing T above 40 K leads to the change in the sign of ΔI_{THz}. Figure 2 also shows plots of d^2I/dV^2 versus V and it can be seen that the $\Delta I_{\mathrm{THz}}(V)$ curve resembles the bias dependence of d^2I/dV^2 for $T>40$ K, suggesting that at these temperatures the diode behaves like a classical rectifier, i.e., the current in the diode follows instantaneously the time-dependent high frequency radiation according to the form of the dc $I(V)$ curve.[16] The correspondence between d^2I/dV^2 and ΔI_{THz} is observed for T up to 80 K and over a wide range of frequencies up to a maximum value of 0.4 THz,[17] above which the photoconductivity decreases, making impossible reliable low-noise measurements of the photocurrent signal.

The rectification effect indicates that for $T>40$ K the mechanism giving rise to NDC is a fast ($\sim 10^{-12}$ s) process. This fast response time is consistent with recent calculations

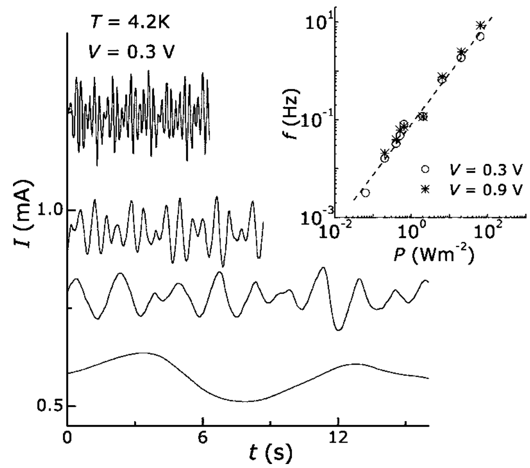

FIG. 3. Time (t) dependence of I at $T=4.2$ K and $V=0.3$ V for a 20 μm diameter mesa diode. For these measurements, the diode was excited with 633 nm laser light. From the bottom to the top, different curves correspond to increasing excitation power densities ($P=2$, 6, 20, and 60 W m^{-2}). The inset shows the P dependence of the frequency f of the current oscillations at $V=0.3$ V and $V=0.9$ V ($T=4.2$ K).

of the ac electron dynamics in $GaAs_{1-x}N_x$ predicting that the maximum response frequency $f_{\max}$ associated with the NDC is governed by the time of ballistic acceleration of electrons to the N level and that this lies in the terahertz frequency range.[6] This finding is also consistent with complementary experiments in which we use the nonlinear characteristics of our diode for frequency multiplication and mixing using superheterodyne detection methods. These studies show that when the diode is driven by signals with well-defined frequencies in the 1–20 GHz range, it leads to harmonic generation of ac current up to frequencies $f\sim 0.1$ THz at $T=77$ K.

We attribute the weakening and broadening of the rectification effect at high T to thermal smearing of the NDC. This arises from the broadening of the energy distribution of the conduction electrons and the increasing number of electrons thermally excited out of the N-induced localized states, thus explaining the thermally activated increase of the dc current at high bias and the corresponding shift of the critical voltage for NDC, see Fig. 1. In contrast, the quenching of the high frequency rectification for $T<40$ K is accompanied by the following unusual observations, all suggesting that the electron dynamics is much slower at these temperatures.

(i) Excitation of the diode by light ($\lambda_{\mathrm{exc}}<1400$ nm) induces oscillations in the low-T current at high dc bias ($V>0.1$ V). The frequency f (<1 Hz) of these LFOs increases with increasing excitation power P, but is only weakly affected by the applied bias, see Fig. 3.

(ii) When the applied bias is increased from zero without light illumination, the conductivity suddenly drops at a critical voltage $V\sim 0.1$ V and remains very low as the bias is increased further. When the bias is then returned to a low value ($V<0.1$ V), the low bias conductivity recovers only very slowly, i.e., the current increases slowly with time until it saturates to a steady value I_0 according to the relation $I=I_0(1-e^{-t/\tau})$, where τ is a characteristic T-dependent recovery time, see Fig. 4. Alternatively, the conductivity can be restored quickly by light of wavelength $\lambda_{\mathrm{exc}}<1400$ nm.

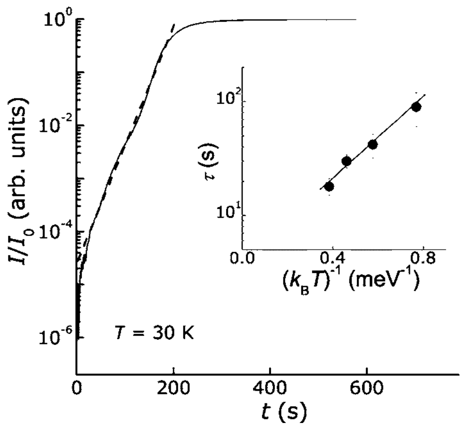

FIG. 4. Time (t) dependence of I at $T=30$ K and $V=0.05$ V for a 20 μm diameter mesa diode. For these measurements, we first applied a bias voltage ($V>0.2$ V) to the diode, then we removed it and measured the t dependence of I at $V=0.05$ V and in the dark. The inset shows the dependence of the recovery time τ on $1/k_BT$. The dashed line is a linear fit to the data.

The slow transients and LFOs observed at low T are similar to those reported previously for semi-insulating (SI) GaAs. These phenomena have been attributed to electric field-enhanced trapping of electrons at localized states associated with EL2-type native defects.[18] Although the precise microscopic nature of this defect is still unclear, there is consensus that it involves an As-antisite (As_{Ga}). In SI-GaAs, hot electrons are captured by the EL2 defect through a multiphonon emission process after which the electron remains "frozen" onto a metastable excited state EL2*. This capture process is accompanied by a pronounced local distortion of the crystal lattice. Spatial variations in the density of trapped electrons also lead to slow high-electric-field domains and LFOs of the current with frequency that increases linearly with the intensity of laser power,[19,20] as observed in our experiment (Fig. 3). We propose that a similar field-enhanced electron trapping can also take place in n-type $GaAs_{1-x}N_x$ at low T (<40 K), although the nature of the trapping center and/or trapping mechanism could be different in this case and may also involve the N atoms.

As shown in Fig. 4, in the temperature range 4–40 K, the recovery time of the current, τ, appears to be thermally activated, i.e., $\tau(T)/\tau(0)=\exp(\varepsilon_A/k_BT)$, where $\varepsilon_A=2\pm1$ meV. This indicates that electrons frozen onto localized states are slowly released by thermal excitation into the CB with a small activation energy ε_A. The positive sign of the photocurrent signal at low T (<40 K) also suggests that the current is enhanced through ionization of the electron traps by the terahertz radiation, see Fig. 2. It seems plausible that the localized states correspond to an electron trap level, $(EL2^*)^{-/0}$, of the metastable EL2* state. In n-type GaAs, the $(EL2^*)^{-/0}$ level lies at about 16 meV above the CB and can be thermally ionized above 40 K,[21] in agreement with model calculations predicting that the energy barrier for this trap is very small.[22] However, we also note that the nature of the electronic states for $GaAs_{1-x}N_x$ is far more complex than in GaAs. In addition to complexes involving As_{Ga} antisites, in $GaAs_{1-x}N_x$, localized electronic levels associated with single N atoms and N aggregates, such as N–N pairs, give rise to localized states just above the CB minimum.[2,3] The admixed character of the $GaAs_{1-x}N_x$ electronic states and the formation of As_{Ga} defects in this material system could enhance the cross section for electron capture, thus explaining why LFOs of the current are not observed in our control samples, i.e., n-type GaAs diodes,[23] but instead can be observed in n-type $GaAs_{1-x}N_x$.

In conclusion, we have shown that the high-electric-field dynamics of conduction electrons in the dilute nitride $GaAs_{1-x}N_x$ alloy is dominated by two competing mechanisms. At low temperature (4–40 K), the dynamics is slow due to a field-enhanced trapping of electrons at localized states, possibly associated with EL2, thus leading to very slow ($f<1$Hz) frequency current oscillations above a critical electric field (>2 kV/cm). For $T>40$ K, electrons frozen onto these states are released by thermal excitation into the CB. In this higher temperature range, we measure a fast electronic response time ($\sim10^{-12}$ s), which we attribute to the resonant interaction of hot electrons with N-induced states in the CB. Further experiments involving diodes optimized for terahertz operation[17] coupled with a quantitative theoretical model of the terahertz dynamics will be needed to assess the use of $GaAs_{1-x}N_x$ in detectors/mixers of terahertz radiation.

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