

## Electron relaxation and transport dynamics in low-temperature-grown GaAs under 1 eV optical excitation

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Electron relaxation and transport dynamics in low-temperature-grown GaAs under 1 eV optical excitation was investigated by femtosecond transient transmission measurement and electro-optical sampling measurement in bulk samples and fabricated devices. An increase in the electron lifetime can be observed when the electron density is higher than  $3 \times 10^{17} \text{ cm}^{-3}$ . This effect is attributed to prolonged electron relaxation due to intervalley scattering of highly excited electrons and associated hot phonon effects. Our conclusion is further supported by bias-dependent studies where intervalley scattering was achieved using high electric fields. © 2003 American Institute of Physics.  
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In recent years, there has been sustained interest in low-temperature-grown (LTG) GaAs based optoelectronics due to their ultrashort response time, high electrical bandwidth, low dark current, and ability to be integrated with other microwave devices such as high electron mobility transistors and antennas.<sup>1,2</sup> Even though most applications have been restricted to the  $\sim 800 \text{ nm}$  range, more and more attention has focused on their potential use for the telecommunications regime ( $1.3\text{--}1.55 \mu\text{m}$ )<sup>3–7</sup> by utilizing midgap defect state to conduction band absorption or two-photon absorption. Recently, ultrahigh speed high power-bandwidth performance has been demonstrated around  $1.3 \mu\text{m}$  with LTG GaAs metal-semiconductor-metal (MSM) traveling-wave photodetectors (TWPDS).<sup>5,6</sup> It is thus important to investigate the electron relaxation and transport dynamics in LTG GaAs under  $1.3 \mu\text{m}$  excitation. Previous pump-probe studies at  $1.56 \mu\text{m}$ <sup>8</sup> have provided information for subband gap carrier dynamics. Compared with  $1.56 \mu\text{m}$  excitation,  $1.3 \mu\text{m}$  excitation generates high-energy hot electrons so more complicated electron relaxation dynamics are expected, and these could strongly influence the carrier transport and device performance. In this letter, we report a study of LTG GaAs under  $\sim 1.3 \mu\text{m}$  excitation by transient transmission measurements in bulk samples and electro-optical (EO) sampling measurements of fabricated devices. An increase in the electron capture time was observed when the electron density was higher than  $3 \times 10^{17} \text{ cm}^{-3}$ . This increase is attributed to prolonged electron relaxation in the conduction band due to intervalley scattering of the highly excited electrons and associated hot phonon effects. Our conclusion is further supported by electric field-dependent studies where intervalley scattering was achieved by high electric fields.

The  $500 \text{ nm}$  thick LTG-GaAs samples under study were grown at  $210^\circ\text{C}$  and annealed at  $600^\circ\text{C}$  in a molecular beam

epitaxy chamber on top of a  $3 \mu\text{m}$  AlGaAs layer for the etch stop and waveguiding. In order to avoid undesired absorption from GaAs substrates during pump-probe measurements, the substrates were removed by a mixed solution of citric acid and hydrogen peroxide (5:1). The LTG GaAs samples with the substrate removed were mounted onto glass substrates directly without any wax or adhesive. With the same wafers, we fabricated MSM TWPDS with varying absorption lengths. The device structure is the same as the one used in Ref. 9. We employed a  $150 \text{ fs}$   $\text{Cr}^{4+}$ :forsterite laser ( $110 \text{ MHz}$  repetition rate) that operated at  $1230 \text{ nm}$  ( $1 \text{ eV}$ ) as the light source for time-resolved measurements. By controlling the average photoexcited carrier density below the space charge screening effect regime ( $< 10^{17} \text{ cm}^{-3}$ ), linear photocurrent response versus  $1230 \text{ nm}$  photoexcitation power can be measured in the devices, indicating that two-photon absorption is not the dominant transition in our measurements. For even higher excitation conditions, the absorption coefficients in the thin films were found to be constant, indicating that our dominant transition should be the midgap defect state to conduction band transitions and the dominant dynamics in our study are due to electrons. With  $1 \text{ eV}$  photon energy, the electrons in the defect state Fermi surface will be excited into the conduction band in the  $\Gamma$  valley with excess energy of around  $300 \text{ meV}$ , which is close to the  $L$  valley minimum. A previous study of LTG GaAs (Ref. 10) using  $2 \text{ eV}$  photoexcitation has indicated the importance of intervalley scattering and the thermalization process in hot carrier relaxation processes.

Figure 1(a) shows traces of measured transient transmission with  $1230 \text{ nm}$  pulses. The electron densities are calculated from the amount of optical absorption power by the method described in Ref. 11, taking into account the Fabry-Pérot effect. A similar measurement was also performed using  $800 \text{ nm}$  femtosecond pulses, and it indicated subpicosecond carrier trapping time, consistent with numerous previous studies.<sup>8</sup> A significant increase in the carrier trapping time

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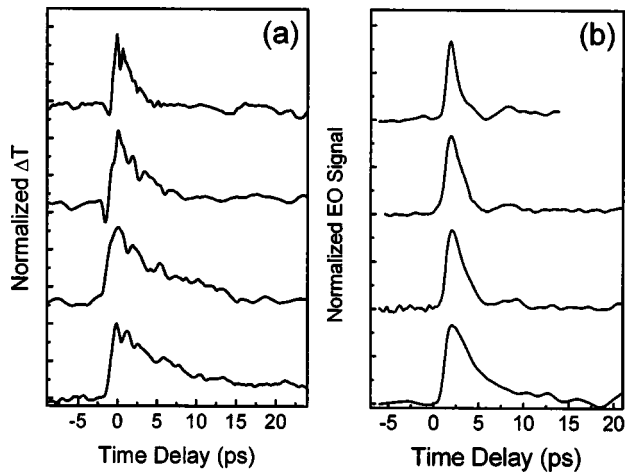


FIG. 1. (a) Traces of normalized transient transmission measured with 1230 nm pump-probe pulses. The electron densities generated are  $1.6$ ,  $3.2$ ,  $4.6$ , and  $5.4 \times 10^{17} \text{ cm}^{-3}$  from top to bottom, with corresponding fitting decay time constant increases from  $0.8$ ,  $1.9$ , and  $4.7$  to  $5.5$  ps. (b) Normalized EO sampling traces of LTG GaAs based MSM TWPDs measured at 1230 nm under fixed 5 V bias under different optical excitations. The average excitation powers and the average electron densities are  $1.3$ ,  $2.6$ ,  $3.1$ , and  $5.7$  mW and  $1.5$ ,  $3.0$ ,  $3.6$ , and  $6.6 \times 10^{17} \text{ cm}^{-3}$ , respectively, from top to bottom. The traces are displayed vertically for clarity.

was not observed until the photoexcited carrier density was higher than  $2 \times 10^{18} \text{ cm}^{-3}$  (from  $0.6$  to  $1.2$  ps). By contrast, the 1230 nm measured traces exhibit much serious broadening with lower photogenerated electron density. When the electron density increased from  $1.6$  to  $5.4 \times 10^{17} \text{ cm}^{-3}$ , the fitted decay time constants dramatically increased from  $0.8$  to  $5.5$  ps. Since we were probing the 1230 nm transition, the measured  $0.8$  ps decay indicates fast electron capture back into defect states combined with fast electron relaxation down to the bottom of the  $\Gamma$  valley, both of which leave the probing area. However with photoelectron density slightly higher than  $3 \times 10^{17} \text{ cm}^{-3}$ , slower electron relaxation should not be induced by defect state saturation based on our 800 nm study. The slow electron relaxation and capture processes under high excitation should thus be attributed to (1) faster electron scattering in  $k$  space with higher electron density that quickly moves the electrons out of the photoexcited region and (2) slower thermalization due to intervalley scattering and hot phonon effects. Intervalley scattering should play an important role in preventing hot electrons from being captured. A previous study<sup>12</sup> using  $1.72$  eV pulses (with less electron excess energy compared with that in our experiment) also indicated that with a hot carrier density of  $1 \times 10^{18} \text{ cm}^{-3}$ , the carrier cooling rate will be reduced due to hot phonon effects.

Even though our pump-probe study indicated an anomalous electron relaxation process with hot electron density higher than  $3 \times 10^{17} \text{ cm}^{-3}$ , this study cannot provide direct information on the electron lifetime. In order to study lifetime behavior with a high density of photoexcited hot electrons under 1 eV excitation, we performed time-resolved EO sampling measurements of MSM TWPDs<sup>5</sup> under 1230 nm femtosecond pulse excitation. The photocurrent measurements of different absorption-length devices indicate an effective absorption constant of  $0.04 \mu\text{m}^{-1}$  (including a confinement factor). With an extremely wide velocity-mismatch

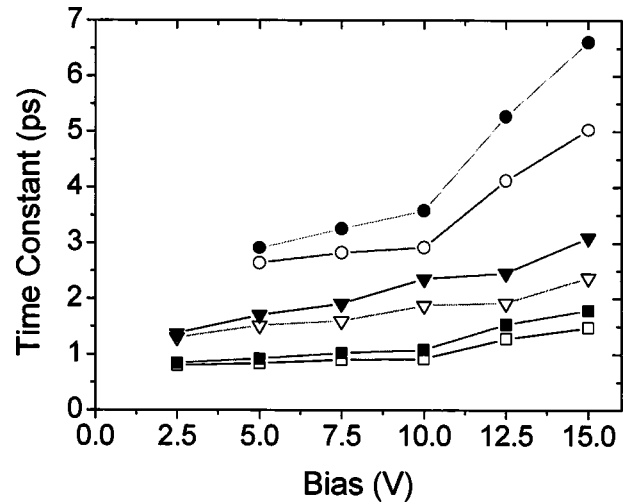


FIG. 2. EO sampling measured time constants (open symbols) and obtained electron lifetime (closed symbols) under  $1.3$  (square),  $3.1$  (triangle), and  $5.7$  mW (circle) excitation as a function of the bias voltage.

bandwidth and a carrier drift time  $\tau_d$  much longer than the carrier lifetime, the impulse current response time  $\tau$  of the measured TWPD is dominated by the electron lifetime  $\tau_e$  in our case (with  $1/\tau = 1/\tau_e + 1/\tau_d$ ),<sup>6</sup> while the devices internal quantum efficiency is determined by the  $\tau_e/\tau_d$  ratio. Figure 1(b) shows the measured EO impulse current response of a  $70 \mu\text{m}$  long LTG GaAs MSM TWPD under 1230 nm excitation with 5 V bias (corresponding to an electric field of  $10 \text{ kV/cm}$  in the center of the guiding mode<sup>6</sup>). The average excitation powers before the coupling lens were  $1.3$ ,  $2.6$ ,  $3.1$ , and  $5.7$  mW with average photocurrents of  $4.3$ ,  $12.1$ ,  $13$ , and  $19 \mu\text{A}$  in the traces from top to bottom. These EO-sampling results also show broadening behavior with an increase in photoelectron density. The fitted decay time constants increased from  $0.8$ ,  $1.4$ , and  $1.6$  to  $2.8$  ps with an increase in electron density. Figure 2 (open symbols) gives the measured  $\tau$  under  $1.3$ ,  $3.1$ , and  $5.7$  mW excitations versus the bias. A dramatic increase in the time constant can be observed when the excitation power was increased to more than 2 mW independent of the bias. Based on a guiding mode calculation<sup>6</sup> and absorption constant measurements, the corresponding carrier densities based on the measured photocurrents can be obtained. However the values obtained are not the electron density generated due to the short electron lifetime. In order to calibrate the photogenerated electron density, one can divide the carrier density by the internal quantum efficiency. By lowering the excitation power to the linear response regime ( $5 \mu\text{A/mW}$  under 5 V bias) where space charge screening is negligible and the bias field is high enough for saturation drift velocity of electrons ( $\sim 50 \text{ km/s}$ ),<sup>13</sup> the generated carrier density can be determined<sup>6</sup> based on an estimate of the electron drift time. These electron densities under high excitation conditions in Fig. 1(b) based on the assumption of a linear absorption are  $1.5$ ,  $3.0$ ,  $3.6$ , and  $6.6 \times 10^{17} \text{ cm}^{-3}$  (for  $1.3$ ,  $2.6$ ,  $3.1$ , and  $5.7$  mW).

Based on the theory<sup>6</sup> that the internal quantum efficiency is determined by the  $\tau_e/\tau_d$  ratio and  $1/\tau = 1/\tau_e + 1/\tau_d$ , we can thus obtain  $\tau_e$  and  $\tau_d$  from the measured EO data (with  $\tau$ ) and the measured photocurrents (with internal quantum efficiency) under high excitation. Figure 2 also shows thus

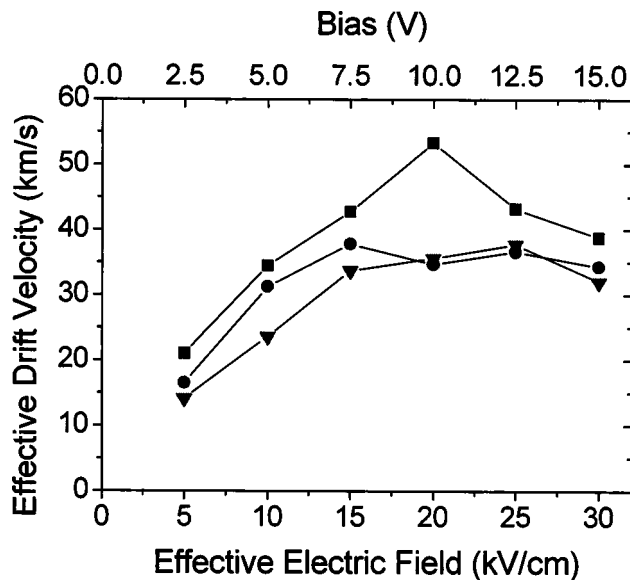


FIG. 3. Electron velocity obtained vs the electric field under 1.3 (square), 2.6 (circle), and 3.1 mW (triangle) excitation.

derived electron lifetime (closed symbols). Slight modification from the measured time constants can be seen, but similar trends remain. We can also obtain the electron drift time (thus the effective drift velocity). Figure 3 shows the electron velocity obtained versus the effective electric field under three different excitation conditions (1.3, 2.6, and 3.1 mW). Please notice that under these excitation conditions, some space charge screening effects will occur according to above electron density estimate. It can be seen that, under these specific excitation conditions, slightly lower saturation velocity  $\sim 4 \times 10^4$  m/s occurs when the electric field is higher than 15 kV/cm and the electron mobility can be estimated to be around  $300 \text{ cm}^2/\text{sV}$ , agreeing with previously published values.<sup>13,14</sup>

For the results below the saturation bias field, the EO measured electron lifetime shows the same trend as that in transient transmission measurements. Compared with the EO sampling data on a similar device under 800 nm excitation (saturating around  $2 \times 10^{18} \text{ cm}^{-3}$ ),<sup>15</sup> our device shows much severe broadening behavior under 1 eV excitation with a lower generated carrier density. Based on the 800 nm experiments,<sup>15</sup> the increase of electron lifetime under 1 eV excitation at a lower electron density ( $3 \times 10^{17} \text{ cm}^{-3}$ ) should not be attributed to the saturation of empty traps. On the other hand, according to the transient transmission measurement data shown in Fig. 1(a), our EO measurements support the fact that with hot electron density higher than  $3 \times 10^{17} \text{ cm}^{-3}$ , the intervalley scattering and hot phonon effects slow down the electron relaxation rate and thus lengthen the electron lifetime. Based on the above discussion, this “hot carrier” phenomenon should also take place in other LTG GaAs devices under normal band-to-band excitation with photon energy much higher than the band gap energy. Serious bandwidth degradation of LTG GaAs photo-

mixers under  $\sim 585 \text{ nm}$  excitation was reported earlier.<sup>16</sup>

It is also reasonable to argue that with a high bias field the resulting hot electrons will also lengthen the electron lifetime and thus degrade device response. In comparing Fig. 2 with Fig. 3, we see a dramatic increase in device response time and electron lifetime when the bias field is higher than the velocity saturation field, thus confirming this. Please note that this increase in lifetime is not due as reported previously to the effect of lowering of the Coulomb barrier,<sup>14</sup> which dominates device response when the electric field is greater than 44 kV/cm (or 25 V in our devices).<sup>17</sup>

In conclusion, electron relaxation and transport dynamics in LTG GaAs under 1 eV excitation were investigated with femtosecond transient transmission measurements and EO sampling measurements in bulk samples and fabricated devices. An interesting increase in electron lifetime was observed when the photogenerated electron density was higher than  $3 \times 10^{17} \text{ cm}^{-3}$ . This increase in electron lifetime is attributed to prolonged electron relaxation in the conduction band due to intervalley scattering of the highly excited electrons and associated hot phonon effects. Our conclusion is further supported by field-dependent studies where intervalley scatterings can be achieved by high electric fields. The results of this study provide information for hot electron dynamics in LTG GaAs as well as for future optimization of ultrafast optoelectronic devices.

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