Field-induced non-equilibrium electron transport in an $In_{0.4}Ga_{0.6}N$ epilayer grown on GaN studied by subpicosecond Raman spectroscopy

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Field-induced non-equilibrium electron transport in an $In_{0.4}Ga_{0.6}N$ epilayer grown on GaN studied by subpicosecond Raman spectroscopy

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Abstract
Field-induced electron transport in an $In_xGa_{1-x}N$ ($x \cong 0.4$) sample grown on GaN has been studied by subpicosecond Raman spectroscopy. Non-equilibrium electron distribution and electron drift velocity due to the presence of piezoelectric and spontaneous fields in the $In_xGa_{1-x}N$ layer have been directly measured. The experimental results are compared with ensemble Monte Carlo calculations and reasonable agreements are obtained.

Gallium nitride (GaN), aluminium nitride (AlN), indium nitride (InN) and their alloys have long been considered as very promising materials for device applications [1, 2]. Semiconductor alloys such as $In_xGa_{1-x}N$ have been successfully used in the fabrication of blue–green light emitting diodes (LEDs) and laser diodes (LDs) [2–7]. Recently, growth of high quality InN as well as $In_xGa_{1-x}N$ has been demonstrated [8–10]. The next natural step is to manufacture high performance InN and $In_xGa_{1-x}N$ electronic devices. In order to improve the design of these devices, knowledge of their electron transport properties is indispensable [11]. In this paper, we report experimental results on subpicosecond Raman studies of electric field-induced electron transport in an $In_xGa_{1-x}N$ ($x \cong 0.4$) epilayer grown on GaN.

The Si doped $In_xGa_{1-x}N$ epilayer of about 0.15 μm thickness used in this work was grown on top of a 1.5 μm GaN epilayer by metal organic chemical vapour deposition (MOCVD). Prior to the GaN growth, a 25 nm thick GaN buffer layer was grown on c-plane sapphire at 550 °C. Subsequent epilayer growth was carried out at 1050 °C for GaN and 710 °C for $In_xGa_{1-x}N$. Trimethylgallium (TMGa) and trimethylindium (TMIn) were used as the precursors. Nitrogen and hydrogen were used as carrier gases for $In_xGa_{1-x}N$ and GaN, respectively. High purity ammonia was used as the active nitrogen source. To vary In content in $In_xGa_{1-x}N$, the TMIn flow rate was varied while other growth parameters were fixed. The $In_xGa_{1-x}N$ epilayer was doped by Si at a flow rate of 0.25 sccm of 10 ppm silane to improve the material quality as well as to enhance the emission efficiency. GaN and $In_xGa_{1-x}N$ growth rates were 3.6 μm h^{-1} and 0.3 μm h^{-1}, respectively. The typical room temperature electron concentration and mobility of $In_xGa_{1-x}N$ alloy are 2×10^{17} cm^{-3} and 160 cm^2 V s^{-1}, respectively, as determined by Hall effect measurements.

The output of the second harmonic of a cw mode-locked YAG laser is used to synchronously pump a dual-jet R6G dye laser. The dye laser, which has a pulse width of FWHM $\cong$ 0.6 ps, photon energy of $\hbar\omega \cong 2.17$ eV and a repetition rate of 76 MHz, was used to both excite and probe the $In_xGa_{1-x}N$ sample. In our transient experiments, since the same laser pulse is used to excite and probe non-equilibrium electron transport, the experimental results represent an average over the duration of the laser pulse. The single-particle scattering (SPS) spectra were taken in the $Z(X, Y)\bar{Z}$ scattering configuration where $X = (100)$, $Y = (010)$, $Z = (001)$ so that only the SPS spectra associated with spin-density fluctuations were detected [12]. The backward-scattered Raman signal is collected and analysed by a standard Raman system consisting of a double spectrometer and a photomultiplier tube. All the data reported here were taken at $T = 300$ K.

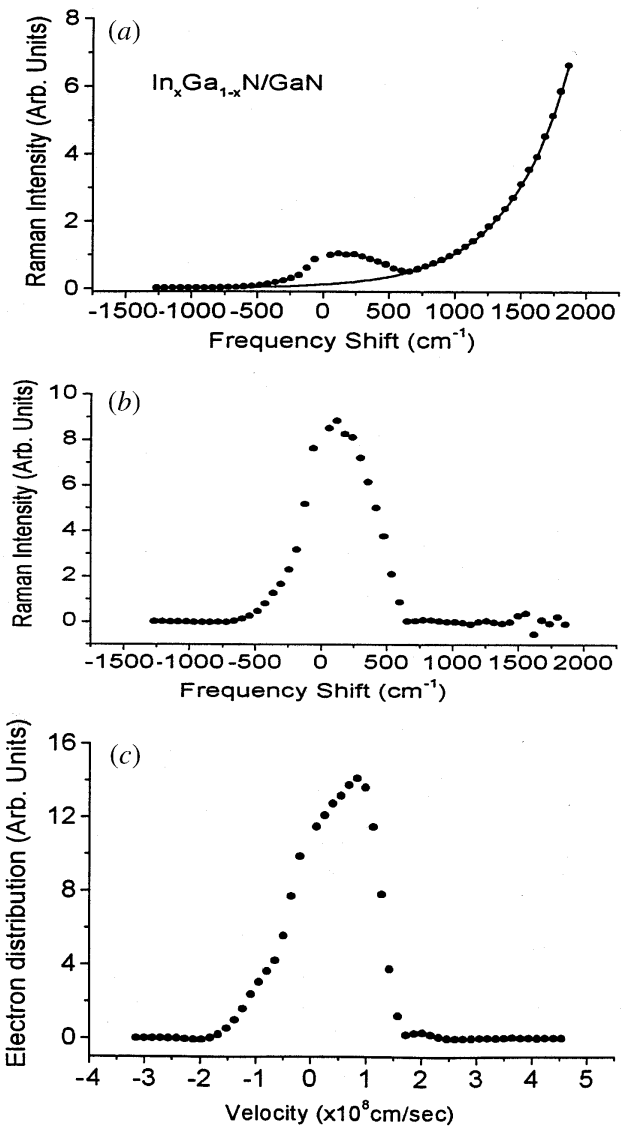

Figure 1. (*a*) A typical SPS spectrum taken at $T = 300$ K and a photoexcited electron–hole pair density of $n \cong 1 \times 10^{18}$ cm^{-3}. The SPS spectrum is found to lie on top of a luminescence background (solid curve) that can be fit very well by an exponential curve; (*b*) The SPS spectrum after subtraction of the luminescence background; (*c*) The electron distribution function obtained from (*b*).

Figure 1(*a*) shows a typical SPS spectrum for an $In_xGa_{1-x}N$ ($x \cong 0.4$) sample taken at $T = 300$ K and for an electron–hole pair density of $n \cong 1 \times 10^{18}$ cm^{-3}. The SPS spectrum sits on a smooth background coming from the luminescence of the E_0 bandgap of $In_xGa_{1-x}N$. Similar to previous studies on other III–V semiconductors such as GaAs, this background luminescence has been found to fit very well by an exponential function [13–15]. The SPS spectrum is obtained by subtracting figure 1(*a*) from this luminescence background. Following the procedure described in detail in [14], this subtracted spectrum (figure 1(*b*)) can then be very easily transformed to an electron distribution function. The electron distribution thus obtained is shown in figure 1(*c*). The intriguing feature worth pointing out is that the electron distribution function has been found to shift towards the wavevector transfer $\vec{q}$ direction—an indication of the presence of an electric field $\vec{E}$ parallel to $-\vec{q}$. The electron distribution has a cut-off velocity of around 1.5×10^8 cm s^{-1}, indicative of the band structure effects and the onset of electron intervalley scattering processes in $In_xGa_{1-x}N$. The electron drift velocity deduced from the measured electron distribution (figure 1(*c*)) is found to be $V_d \cong (3.8 \pm 0.4) \times 10^7$ cm s^{-1}.

We have also carried out an ensemble Monte Carlo (EMC) simulation [16] for the transport of the photo-excited carriers in $In_xGa_{1-x}N$. Here, we treat polar optical phonons, acoustic phonons, intervalley phonons and dislocation scattering. For dislocation scattering [17, 18], we assumed that a defect density of 10^8 cm^{-2} existed in the $In_xGa_{1-x}N$ layer; however, it is found that because of the presence of much more efficient inelastic scattering processes, this elastic defect scattering process can affect the low field mobility but is not important for the high field transient experiments carried out here. Disorder-induced scattering due to In concentration fluctuations in $In_xGa_{1-x}N$ is not included in the EMC simulation because it is an elastic scattering process that does not affect the high field transport [16]. Our EMC calculations predict that the electron drift velocity under our experimental conditions is $V_d = 3.5 \times 10^7$ cm s^{-1}. This result is in reasonable agreement with the experimental value quoted above. Therefore, a simple physical picture for our work is that electron–hole pairs are photoinjected into the InGaN layer. These carriers are subject to the built-in electric field in the InGaN layer and their transport is detected by our Raman spectroscopy.

In conclusion, we have studied field-induced electron transport in an $In_xGa_{1-x}N$ ($x \cong 0.4$) sample grown on GaN by subpicosecond Raman spectroscopy. Non-equilibrium electron distribution and electron drift velocity due to the presence of piezoelectric and spontaneous fields in the $In_xGa_{1-x}N$ layer have been directly measured. The experimental results are compared with ensemble Monte Carlo calculations and reasonable agreements are obtained.

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