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Hot-electrons and negative differential conductance in $GaAs_{1-x}N_x$

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We show that the manipulation of the band structure of GaAs by the incorporation of a small amount of N provides a powerful means of tailoring the dynamics of conduction electrons. We observe and model theoretically a strong negative differential velocity (NDV) effect that occurs when electrons are accelerated by an electric field in the highly nonparabolic conduction band of Ga(AsN). The NDV effect is fundamentally different from that occurring in superlattice Bloch oscillators and transferred electron devices, and is of potential interest for emitters and detectors of high-frequency radiation.

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The incorporation of low concentrations of N ($x=0\%-5\%$) in GaAs leads to a number of unusual alloy phenomena and electronic properties, which have increased the power and scope of band-structure engineering as a tool for the design of electronic devices.[1] The large electronegativity of the N atoms combined with the stretching and compression of neighboring bonds in GaAs strongly perturbs the band structure properties of the host crystal. N-impurities and N-clusters act to “disrupt” the extended Bloch states of GaAs at characteristic resonant energies in the conduction band.[2–5] This leads to a strongly modified energy-wave-vector $\varepsilon(k)$ dispersion relation of the conduction electrons and to a large redshift of the band gap.[1–5]

Magneto-tunnelling spectroscopy experiments have been used to probe directly the unusual form of the $\varepsilon(k)$ curves of $GaAs_{1-x}N_x$ at low $x(\sim 0.1\%)$ and to demonstrate that the admixing and hybridization of the extended GaAs conduction band states with the localized single N-impurity levels causes a splitting of the conduction band into highly nonparabolic hybridized subbands E_- and E_+,[4] thus validating the two-level band-anticrossing (BAC) model at low x.[2,3,5] Of particular interest is the formation of a fully developed energy gap between E_- and E_+ and the unusual form of the lower energy subband in which an inflection point occurs in $\varepsilon(k)$ [see Fig. 1(a)].

In this paper, we demonstrate that this unusual band structure can be tailored and exploited to realize a nonlinear device in which electrons are accelerated by an electric field, F, up to and beyond the inflection point in $\varepsilon(k)$, thus leading to a negative differential drift velocity (NDV) effect, which has a fundamentally different physical origin compared to that occurring in transferred-electron devices[6,7] and superlattice heterostructures.[8] We analyze the motion of electrons accelerated by a large electric field in the nonparabolic conduction band of $GaAs_{1-x}N_x$ and show that the manipulation of the conduction band of GaAs by the incorporation of a low N content provides a flexible and powerful means of controlling the dynamics of electrons at high electric fields. The prediction of a strong NDV effect is confirmed experimentally by high electric field measurements on an n-type modulation doped $GaAs_{1-x}N_x$ quantum well layer with $x=0.1\%$.

Figure 1(b) shows the group velocity, $v_g(k)=\hbar^{-1}(\partial\varepsilon/\partial k)$, for electrons in the lower energy hybridized subband, E_-, of $GaAs_{1-x}N_x$ calculated according to a two-level BAC model.[2,3] The group velocity has a maximum at the inflection point of the $\varepsilon(k)$ curve and falls off rapidly at higher k values. The physics giving rise to this dependence is significantly different from that involved in crystals or superlattice

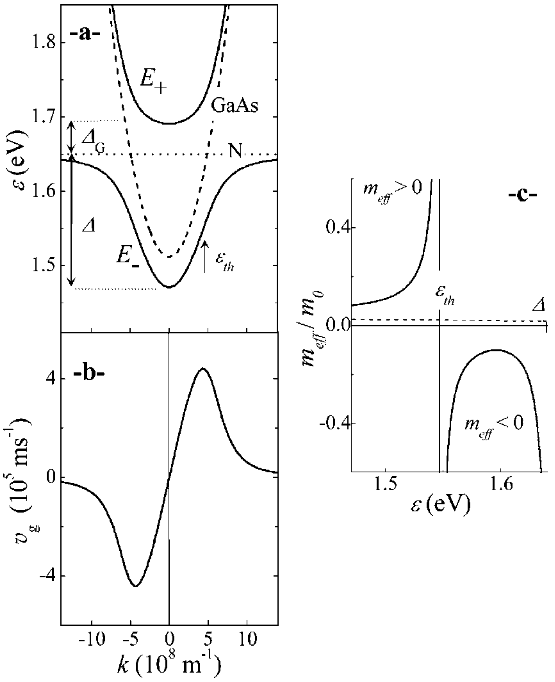

FIG. 1. (a) Energy-wave-vector dispersion relation, $\varepsilon(k)$, for subbands E_- and E_+ of $GaAs_{1-x}N_x(x=0.1\%)$, calculated according to a two-level BAC model ($T=4.2$ K). ε_{th} is the energy of the electron at the inflection point of the $E_-(k)$ curve, Δ is the energy width of the E_- subband and Δ_G is the energy gap between subbands E_- and E_+. (b) k dependence of the group velocity for electrons in the lower energy subband E_- of bulk $GaAs_{1-x}N_x$. (c) ε dependence of the electron effective mass, m_{eff}, normalized to the free electron mass, m_0.

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heterostuctures, in which electrons are *coherently* Bragg reflected at the boundary of the Brillouin zone, thus leading to Bloch oscillations and a periodic dependence of v_g on k. In $\mathrm{GaAs}_{1-x}\mathrm{N}_x$, the unusual form of the $v_g(k)$ curve arises from the resonant interaction between the conduction band states of GaAs and the *randomly positioned* N atoms, which leads to strong localization of electrons at energies of ~1.6 eV above the valence band edge and at relatively modest wave vectors, considerably smaller than the size of the Brillouin zone. This is expected to affect significantly the dynamics of conduction electrons when an applied dc or ac electric field accelerates them into this range of energy and k vectors. In this paper we focus on the electron dynamics in a static applied electric field, F.

We use a semiclassical model to describe the motion of the conduction electrons. The dependence on time, t, of the average energy, $\bar{\varepsilon}(t)$, and of the drift velocity, $v_d(t)$, is derived by solving the dynamical balance equations,[9–11]

$$\frac{dv_d}{dt} = \frac{qF}{m_{\mathrm{eff}}(\bar{\varepsilon})} - r_v v_d, \tag{1}$$

$$\frac{d\bar{\varepsilon}}{dt} = qFv_d - r_i\bar{\varepsilon}, \tag{2}$$

where $q(=-e)$ is the electron charge, $r_v = r_i + r_e$ is the relaxation rate of the velocity, which includes the energy relaxation rate, r_i, and the elastic scattering rate, r_e, and $m_{\mathrm{eff}}(\bar{\varepsilon})$ is the energy-dependent electron effective mass derived from the functional form of the $E_-(k)$ dispersion given by the BAC model [see Fig. 1(c)].

The steady state solution of Eqs. (1) and (2) leads to the following relations: $v_d = r_i\bar{\varepsilon}/qF$ and $\bar{\varepsilon} = (qF)^2/m_{\mathrm{eff}}(\bar{\varepsilon})r_v r_i$, from which we derive numerically the drift velocity-field characteristic, $v_d(F)$. According to this model, for any value of F, the average electron energy $\bar{\varepsilon}$ is always smaller than $\varepsilon_{\mathrm{th}}$, the energy of the electron at the inflection point of the $E_-(k)$ curve [see Fig. 1(a)]. For $\bar{\varepsilon} < \varepsilon_{\mathrm{th}}$, the electron effective mass can be approximated by $m_{\mathrm{eff}}(\bar{\varepsilon}) = m_{\mathrm{eff}}(0)/(1-\bar{\varepsilon}/\varepsilon_{\mathrm{th}})$. Using this expression, we find that $v_d(F)$ reduces to the simple form $v_d(F) = \mu F/[1+(F/F_T)^2]$, where $\mu = e m_{\mathrm{eff}}(0)^{-1} r_v^{-1}$ is the low-field mobility, $F_T = p_N(r_v r_i)^{1/2}(1+D)^{1/4}/2e$ is the critical field corresponding to a peak drift velocity $v_d^M = p_N(r_i/r_v)^{1/2}(1+\sqrt{1+D})/8m(1+D)^{1/4}$. Here $p_N = \sqrt{2m\Delta_N}$, Δ_N is the energy position of the N level relative to the conduction band minimum of GaAs ($\Delta_N = 0.13$ eV), m is the electron effective mass of GaAs at $k=0$, $D = 4V_{NM}^2/\Delta_N^2$ and $V_{NM} = C_{NM}x^{1/2}$ ($C_{NM} = 2.7$ eV) is the coupling matrix element between the N level and the conduction band states of GaAs in the BAC model.[2,3]

Figure 2(a) shows the $v_d(F)$ curves for $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ ($x = 0.1\%$) calculated numerically for different values of r_e and r_i. In the limit of small electric fields, the drift velocity has a linear dependence on F, i.e., $v_d(F) = \mu F$. For higher fields, the shape of the $v_d(F)$ curve deviates from the simple linear behavior showing a peak drift velocity v_d^M at F_T, followed by a strong decrease of v_d for increasing F. The velocity is totally quenched in the absence of inelastic scattering, i.e., $v_d \rightarrow 0$ as $r_i \rightarrow 0$, and/or in the presence of strong elastic scattering, i.e., $v_d \rightarrow 0$ as $r_e \rightarrow \infty$. Increasing values of r_e leads to an increasing critical field F_T, while in the limit of $r_i \rightarrow 0$, $F_T \rightarrow 0$.

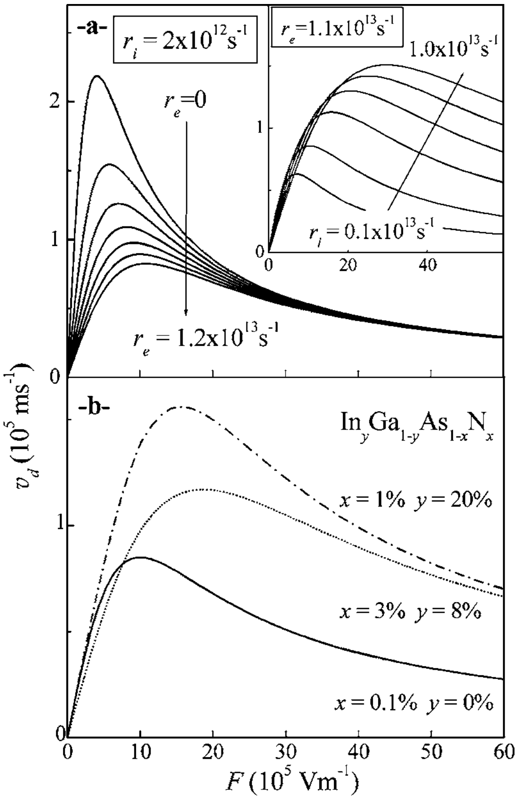

FIG. 2. (a) Drift velocity-field characteristics $v_d(F)$ for $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ ($x = 0.1\%$) calculated using the model described in the text for different values of the elastic scattering rate r_e and for an inelastic scattering rate $r_i = 0.2\times10^{13}\ \mathrm{s}^{-1}$. The value of r_e is increased from 0 to $1.2\times10^{13}\ \mathrm{s}^{-1}$ in steps of $0.2\times10^{13}\ \mathrm{s}^{-1}$. In the inset, the $v_d(F)$ curves are calculated for $r_e = 1.1\times10^{13}\ \mathrm{s}^{-1}$ and for $r_i = 0.1$, 0.2, 0.4, 0.6, 0.8, and $1.0\times10^{13}\ \mathrm{s}^{-1}$. (b) Representative $v_d(F)$ curves for $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}_{1-x}\mathrm{N}_x$ calculated for $r_i = 0.2\times10^{13}\ \mathrm{s}^{-1}$ and $r_e = 1.1\times10^{13}\ \mathrm{s}^{-1}$.

This simple model for the drift velocity calculation gives us a clear physical picture of the NDV effect, but it neglects the energy distribution of the electrons. This simplification is justified by our analysis of the energy distribution function derived from the Boltzmann equation. This indicates that increasing electric fields causes a broadening of the distribution function in momentum space. However, the two approaches lead to very similar velocity-electric field curves. Also, our model assumes a functional form for the $E_-(k)$ dispersion given by the BAC model[2,3] and does not describe explicitly the increasingly localized character of the electronic states as their energy approaches that of the N level.[4,5] Nevertheless, the form of $v_d(F)$ is only slightly affected by the simplifying assumption that the subband extends well beyond the inflection point in the $E_-(k)$ curve, since our analysis shows that very few electrons reach the low-velocity k states beyond this point and the average electron energy $\bar{\varepsilon}$ is smaller than $\varepsilon_{th} \approx \Delta/2$, where Δ is the energy width of the E_- subband.

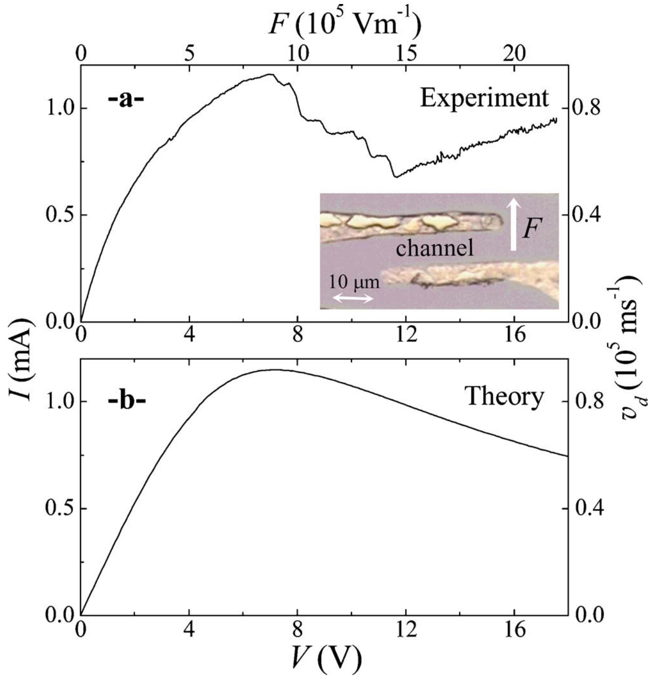

FIG. 3. (Color online) (a) Measured current-voltage characteristic, $I(V)$, at $T=77$ K of a conducting channel of width, $W=25\ \mu\mathrm{m}$ and length, $L=8\ \mu\mathrm{m}$, made from an n-type modulation doped $\mathrm{GaAs}_{1-x}\mathrm{N}_x(x=0.1\%)$ QW layer. A white light bulb was used to illuminate the sample to increase the carrier concentration in the QW. Inset, optical microscope image of the device. The horizontal fingers correspond to the electrodes. (b) $I(V)$ curves calculated using the semiclassical model and parameters described in the text.

To explore the possibility of NDV in $\mathrm{GaAs}_{1-x}\mathrm{N}_x$, we prepared a modulation-doped n-type $\mathrm{GaAs}_{1-x}\mathrm{N}_x/\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ quantum well (QW) heterostructure with $x=0.1\%$, grown by molecular-beam epitaxy on a semi-insulating, (100)-oriented GaAs substrate. Measurements on standard Hall bars at low applied electric fields gave an electron mobility $\mu=0.2\ \mathrm{m^2/V\,s}$ at $T=4.2$ K ($\mu=0.1\ \mathrm{m^2/V\,s}$ at $T=300$ K) and a sheet electron density $n_e=(3\pm1)\times10^{15}\ \mathrm{m^{-2}}$.[12]

The inset of Fig. 3(a) shows the structure used to study the NDV effect. The current, I, flows across a channel of length, $L=8\ \mu\mathrm{m}$ and width, $W=25\ \mu\mathrm{m}$. As shown in Fig. 3(a), the low-temperature ($T=77$ K) current-voltage characteristics, $I(V)$, of this type of device exhibits an ohmic behavior at low bias, followed by a peak in the current and an extended region of negative differential conductance (NDC) with pronounced steplike features consistent with space charge instabilities. Measurements on several devices exhibited the same NDC effect (see, for example, data in Fig. 4). This was observed up to temperatures of about 150 K. For $T>150$ K, the current intensity decreases and the NDC disappears. We attribute this temperature dependence to thermal escape of electrons from the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ QW channel into traps in the surrounding material.

To test if carrier ejection out of the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ QW layer is responsible for the NDC effect, we have studied the dependence of the NDC on a magnetic field, B, up to 12 T applied parallel to the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ QW channel and to the current. Such a field would tend to decrease the probability of electrons tunnelling out of the channel as it provides an additional confinement potential. As shown in the inset of Fig. 4, for this magnetic field configuration, we observed no significant change of the current intensity, nor of the NDC, thus supporting the idea that scattering of electrons out of the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ layer is not the origin of the NDC.

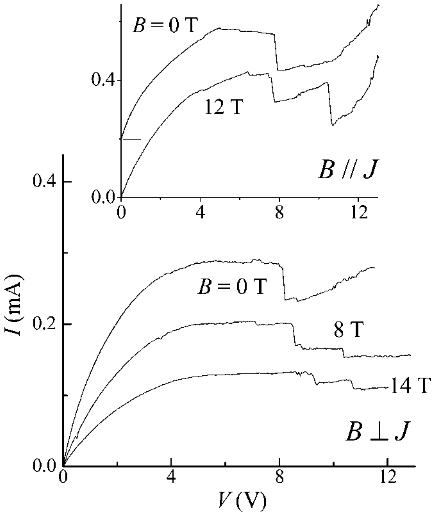

FIG. 4. Measured current-voltage characteristics, $I(V)$, at $T=77$ K versus magnetic field, B, applied perpendicular to the QW plane. A white light bulb was used to illuminate the sample to increase the carrier concentration in the QW. Inset, $I(V)$ at 77 K versus magnetic field, B, applied parallel to the QW plane and to the current.

To probe further the electron motion, we have also measured the effect on the NDC of a magnetic field, B, applied perpendicular to the QW plane. In this geometry, due to the action of the Lorentz force, an electron tends to increase its momentum component in the direction perpendicular to the current, with a corresponding loss of kinetic energy for motion along the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ channel. This implies that, for increasing B, a larger applied bias is required to sustain the conduction, thus shifting the NDC region in the $I(V)$ curve to higher bias as also observed in our experiment (see Fig. 4).

To test for possible effects arising from lattice heating when the device is biased in the voltage range of NDC, we studied the bias dependence of the band-gap energy of $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ by measuring the interband photocurrent spectrum of our devices. These measurements were made at the same bath temperature, 77 K, as that for the data shown in Figs. 3 and 4. We found no detectable redshift of the band-gap energy with increasing bias thus indicating that the lattice temperature rise in the NDC bias range is small. These measurements are consistent with our estimate of the temperature rise in the channel caused by Joule heating. For the maximum power dissipated in our device (~15 mW), we estimate that the temperature rise is less than 5 K. This estimate is based on the thermal conductivity of GaAs ($4\ \mathrm{W\,cm^{-1}\,K^{-1}}$ at 77 K) (Ref. 13) and a standard model[14] for heat conduction from the $\mathrm{GaAs}_{1-x}\mathrm{N}_x$ channel through the large area ($1\ \mathrm{mm}^2$) and thick ($300\ \mu\mathrm{m}$) semi-infinite GaAs substrate, which is well heat sunk to the metallic sample holder at 77 K. This model neglects the additional heat loss by conduction through the top surface of the device and through the metallic leads. So in reality the temperature rise should be significantly smaller than 5 K.

The measured $I(V)$ curves are described accurately in terms of the $v_d(F)$ characteristics predicted by our model and are therefore fully consistent with our analayis of the NDC effect in $\mathrm{GaAs}_{1-x}\mathrm{N}_x$. In Fig. 3(b) we plot the $I(V)$ curve calculated from $v_d(F)$ using the relations $V=FL$ and $I=n_e e v_d W$, and the following values of scattering rates, $r_i=0.2\times10^{13}\ \mathrm{s}^{-1}$ and $r_e=1.1\times10^{13}\ \mathrm{s}^{-1}$. These values give a low-field electron mobility $\mu=em_{\mathrm{eff}}(0)^{-1}r_v^{-1}=0.17\ \mathrm{m}^2/\mathrm{V\,s}$ in the ohmic regime of the $I(V)$ curve, which corresponds with that obtained from Hall measurements in standard Hall bars ($\mu=0.17\ \mathrm{m}^2/\mathrm{V\,s}$ at $T=77$ K). The value of r_i is close to that measured in GaAs (see, for example, Ref. 15), while the large r_e is consistent with strong elastic scattering due to collisions of electrons by the random distribution of N atoms.[12,16] The strong elastic scattering does not quench the NDC; it simply shifts it to high applied electric fields. Our experiment and analysis indicate that an electric field $F_T=9\times10^5\ \mathrm{V\,m}^{-1}$ is needed to accelerate electrons to their peak drift velocity $v_d^M=0.9\times10^5\ \mathrm{m\,s}^{-1}$. The value of v_d^M is smaller than the maximum group velocity at the inflection point, $v_g^M=4\times10^5\ \mathrm{m\,s}^{-1}$,due to the strong scattering. As shown in Figs. 3(a) and 4, the measured current increases at high electric fields, beyond the NDC region. We attribute this increase to Zener tunnelling of electrons between the E_- and E_+ subbands. We estimate that due to the large energy gap Δ_G between the two subbands ($\Delta_G\geqslant50$ meV for $x\geqslant0.1\%$), this effect becomes important only at electric fields larger than those required to reveal the NDV effect.

In conclusion, we have shown that the unusual fragmented band structure of GaAs doped with a small concentration of N atoms (0.1%) provides a powerful means of tailoring the dynamics of conduction electrons in a semiconductor. We have predicted and observed a strong NDV effect when electrons are accelerated by large electric fields in the highly nonparabolic conduction band of $\mathrm{GaAs}_{1-x}\mathrm{N}_x$. Finally, we suggest that the additional design parameter (y) provided by the $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}_{1-x}\mathrm{N}_x$ system could be used further to enhance the NDV effect and to adjust the critical field, see Fig. 2(b), which also indicates that significantly higher peak velocities could be achieved by the incorporation of a small amount of In. This is of potential interest for emitters and detectors of high-frequency (GHz–THz) radiation.[17,18] Our study is also of general interest as it concerns the electron dynamics in an unusual material system, which could find interesting applications in other high-field devices such as quantum cascade lasers.[19]

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