Electron effective mass and Si-donor binding energy in $GaAs_{1-x}N_x$ probed by a high magnetic field

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We study the magnetoresistance of the dilute nitride alloy $GaAs_{1-x}N_x$ in magnetic fields up to 47 T. We observe a strong magnetophonon resonance effect and a large transverse magnetoresistance, which provide the means of measuring the N-induced enhancement of the electron effective mass and of investigating the magnetic freeze-out of conduction electrons on Si donors in $GaAs_{1-x}N_x$.

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I. INTRODUCTION

The dilute nitride alloy $GaAs_{1-x}N_x$ belongs to a class of highly mismatched alloys[1,2] that in recent years have opened up interesting research areas in semiconductor physics with prospects for a wide range of applications including long wavelength (1.3–1.55 μm) lasers,[3] solar cells,[4] and high-frequency (terahertz) electronics.[5] In these device structures, the concentration of N atoms is used to fine-tune fundamental electronic properties, such as the principal energy gap,[1] the effective mass,[6] and group velocity[7] of the conduction electrons. The incorporation of N in GaAs also gives rise to a unique alloy phenomenon: Single N atoms and N aggregates, such as impurity N-N pairs and higher-order clusters, form strongly localized states, which hybridize with the extended band states of GaAs and give rise to an "amalgamated" and fragmented conduction band made of strongly admixed states.[8,9] An important manifestation of this phenomenon is the strong reduction of the electron mobility with increasing N content.[10,11] Despite a rapidly expanding body of work on the optical and electrical properties of this material system, there have been relatively few investigations of its magnetoconductivity.[12–15]

In this work, we study the magnetoresistance of the Si-doped dilute nitride alloy $GaAs_{1-x}N_x$ in the presence of a quantizing magnetic field $\mathbf{B}$ applied either parallel ($\mathbf{B}_\parallel$) or perpendicular ($\mathbf{B}_\perp$) to the direction of electric field $\mathbf{E}$. At low temperature ($T<150$ K), we observe a strong magnetophonon resonance (MPR) effect.[16] This corresponds to an oscillatory variation of the magnetoresistance as a function of magnetic field, which is caused by scattering of electrons between Landau levels (LLs) mediated by longitudinal optical (LO) phonons. We observe resonances in the magnetoresistance as a function of B in both field configurations. The resonances occur when a multiple of the LL spacing is equal to the LO phonon energy, i.e., when $\omega_{LO}=i\omega_c$, where ω_{LO} and $\omega_c=eB/m_e^*$ are the LO phonon and cyclotron angular frequencies, i is an integer, and m_e^* is the electron effective mass.[16] When the phonon energy involved in the MPR resonance is known, the value of m_e^* can be derived from the period, $\Delta(1/B)$, of the magnetoresistance oscillations, i.e., $m_e^*=e/\omega_{LO}\Delta(1/B)$. We also observe that the conduction electrons can freeze-out onto Si-donor bound states in the presence of a strong transverse magnetic field, leading to a transition from metalliclike to hoppinglike conduction and to a large magnetoresistance. These observations allow us to measure the N-induced enhancement of the electron effective mass and the associated increased binding of electrons onto Si-donor impurities in $GaAs_{1-x}N_x$. Although a N-induced enhancement of the binding energy ε_{Si} was predicted in previous work,[17] to our knowledge no supporting experimental evidence has been reported previously.

II. SAMPLES

For this study, we use n^+-n-n^+ $GaAs/GaAs_{1-x}N_x/GaAs$ heterostructures grown by molecular beam epitaxy on (100)-oriented Si-doped GaAs substrates [Fig. 1(a)]. The growth sequence is as follows: a 0.2-μm-thick n^+ GaAs buffer layer (n^+: 2×10^{18} cm^{-3}), an n-type $GaAs_{1-x}N_x$ layer ($x=0.1\%$) of thickness $L=0.6$ μm, doped with Si to 1×10^{17} cm^{-3}; the growth was completed with a 0.5-μm-thick n^+ GaAs cap layer (n^+: 2×10^{18} cm^{-3}). Our samples were processed into circular mesa diodes with diameter $d=20$ μm. Here, we focus on samples with relatively low concentrations of N ($x=0.1\%$) and with electron mobility $\mu\sim0.2$ m^2 V^{-1} s^{-1} at low ($T=2$ K) and room temperatures. We have also investigated a number of structures with different N contents ($x>0.1\%$) or n-type doping (Si: 1×10^{18} cm^{-3} and Se: 1×10^{19} cm^{-3}) of the $GaAs_{1-x}N_x$ layer.[18] For these structures the electron mobility is smaller and is limited by strong electron scattering at high x.[10,11,14,15] We find that the transverse magnetoresistance of these structures is small ($\Delta R/R<10\%$ at $B=10$ T), as was also reported for the low-mobility dilute nitride alloy

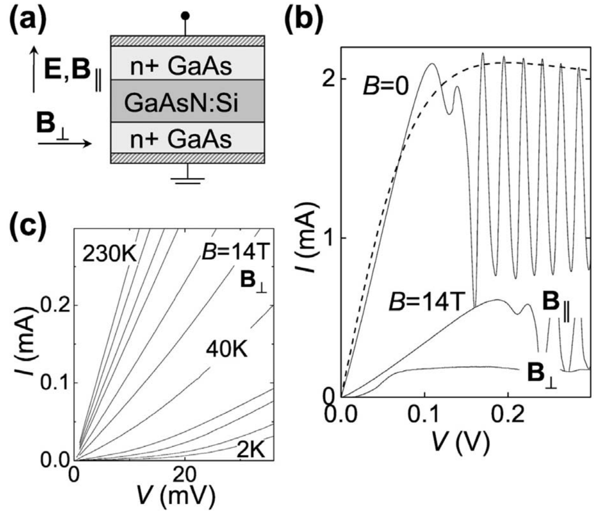

FIG. 1. (a) Schematic diagram of the diode and orientation of electric (**E**) and magnetic (**B**) field. (b) I(V) curve for the $GaAs_{1-x}N_x$ (x=0.1%) diode at $\mathbf{B}=0$ and in $\mathbf{B}_\perp$ and $\mathbf{B}_\parallel$ with B=14 T (T=4.2 K). The dashed line is a fit to the data at B=0 using the semiclassical model described in the text. (c) T dependence of the $I(V)$ curve at B=14 T and $\mathbf{B}_\perp$ (T=2, 10, 20, 30, 40, 50, 60, 80, 100, 150, and 230 K).

$In_yGa_{1-y}As_{1-x}N_x$ in magnetic fields B up to 10 T.[12,13] In this paper, we consider larger quantizing magnetic fields up to 14 T (static) or 47 T (pulsed) for which $\mu B \gg 1$. These strong fields also provide values of $\hbar\omega_c$, which can exceed the energy of longitudinal optical phonons in GaAs ($\hbar\omega_{LO}$ =36.7 meV).[19]

III. RESULTS AND DISCUSSION

A. Longitudinal and transverse magnetoresistance

Figure 1(b) shows the low-temperature (T=4.2 K) current-voltage, $I(V)$, characteristics of our device at $\mathbf{B}=0$ and in a magnetic field B=14 T applied parallel ($\mathbf{B}_\parallel$) or perpendicular ($\mathbf{B}_\perp$) to **E**. At $\mathbf{B}=0$, the $I(V)$ curve exhibits ohmic behavior up to a threshold voltage beyond which it enters a regime of negative differential conductance (NDC) and of instability in the current. The $I(V)$ curve is strongly modified in $\mathbf{B}_\perp$. In this configuration, the magnetic field suppresses the current at low bias voltages below a threshold value $V \sim 0.05$ V. The effect of B on the current and NDC is weaker in the $\mathbf{B}_\parallel$ geometry.

The B dependence of the magnetoresistance, $R=V/I$, in the $\mathbf{B}_\perp$ configuration is shown in Fig. 2 for different temperatures and low applied biases (V=0.01 V). In this geometry and at low temperature, the value of R can increase by more than a factor of 10^2 in a field of 14 T. This effect becomes weaker at higher T [Figs. 1(c) and 2]. We also observe an oscillatory effect in the magnetoresistance at higher magnetic fields and $V > 0.03$ V [see Fig. 3(a)]. Data shown in this figure were obtained using a nondestructive pulsed (~40 ms) magnetic field system up to 47 T and the measurements were taken during the down sweep of B. To reveal the oscillatory component of $R(B)$, in Fig. 3(a) we also plot the

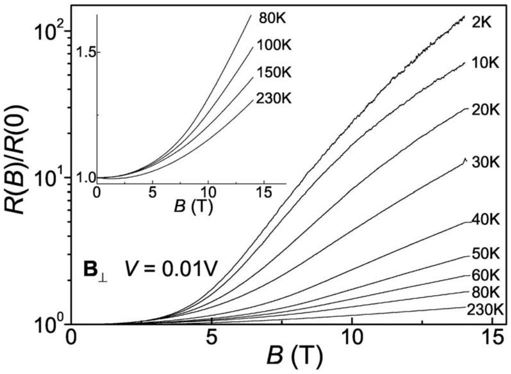

FIG. 2. B dependence of the transverse magnetoresistance at V=0.01 V and different T. The inset shows the transverse magnetoresistance at high T.

second derivative $-d^2R/dB^2$. The maxima in this quantity correspond to the resonant peaks in the oscillatory component of $R(B)$. By comparing the traces for $\mathbf{B}_\parallel$ and $\mathbf{B}_\perp$, it can be seen that maxima in $R(\mathbf{B}_\parallel)$ correspond closely to minima in $R(\mathbf{B}_\perp)$ [Fig. 3(a) and 3(b)]. Note that in the $\mathbf{B}_\perp$ geometry the magneto-oscillations cannot be observed at high B (>25 T) and/or low bias ($V < 0.03$ V). Under these conditions, the transverse magnetoresistance shows a large increase with B, making impossible reliable low-noise measurements of the relatively weak magneto-oscillations. The magneto-oscillations in $R(B)$ are observed in $\mathbf{B}_\parallel$ and $\mathbf{B}_\perp$ up to a temperature $T \sim 100$ K, above which both the oscillatory and monotonic magnetoresistance effects become very weak [Figs. 4 and 5].

B. Magnetophonon resonance and electron cyclotron mass

The form of the $I(V)$ curves at $\mathbf{B}=0$ reveals a negative differential velocity effect, i.e., the decrease of the electron

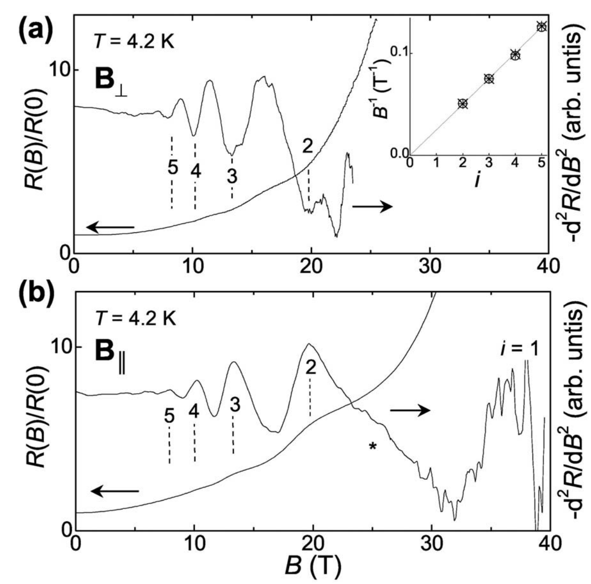

FIG. 3. B dependence of R and $-d^2R/dB^2$ at T=4.2 K and V=0.09 V in (a) $\mathbf{B}_\perp$ and (b) $\mathbf{B}_\parallel$. The inset of part (a) shows positions in $1/B$ of the minima and maxima in $-d^2R/dB^2$ as a function of i at T=4.2 K. Circles and stars correspond, respectively, to $\mathbf{B}_\parallel$ and $\mathbf{B}_\perp$. The line is a linear fit to the data.

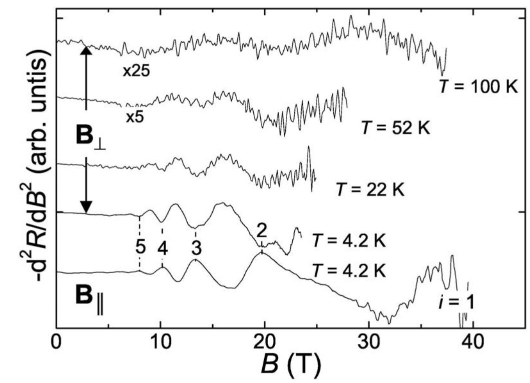

FIG. 4. B dependence of $-d^2R/dB^2$ in $\mathbf{B}_\perp$ (T=4.2, 22, 52, and 100 K) and $\mathbf{B}_\parallel$ (T=4.2 K).

drift velocity v_d with increasing E, which occurs when electrons are accelerated in the nonparabolic conduction band of $GaAs_{1-x}N_x$.[7] The $v_d(E)$ curve is described by the relation $v_d(E)=\mu E/[1+(E/E_T)^2]$, where μ is the low-field mobility and E_T is the critical field for NDC.[5] The overall form of the $I(V)$ curve can be explained by considering two contributions to the electronic conduction: The first is due to the "background" free electron density n_0 in the $GaAs_{1-x}N_x$ layer at V=0; the second contribution is the mobile space charge arising from the additional electrons, density n_s, injected into the $GaAs_{1-x}N_x$ from the negatively biased n^+ GaAs-emitter layer.[20,21] We calculate the current density by solving the equation for the drift current, $J=(n_0+n_s)ev_d$, and Poisson's equation, $\partial E/\partial x=en_s/\kappa$, where κ is the dielectric permittivity of the lattice. The dashed line in Fig. 1(b) shows the $I(V)$ curve calculated by setting E_T=2 kV/cm, μ=0.20 m^2/V s, and $n_0=2\times10^{15}$ cm^{-3}. The value of n_0 is smaller than the nominal Si concentration (1×10^{17} cm^{-3}). The electron mobility agrees with that obtained from Hall measurements on our modulation-doped $GaAs_{1-x}N_x$ quantum wells with x =0.1% (μ=0.20 m^2/V s at T=4.2 K) (Ref. 15) and with the values obtained by others on similar structures.[11] Its value increases by less than a factor of 2 when T is increased from 4 to 100 K and, as T is increased further, it remains practically constant.

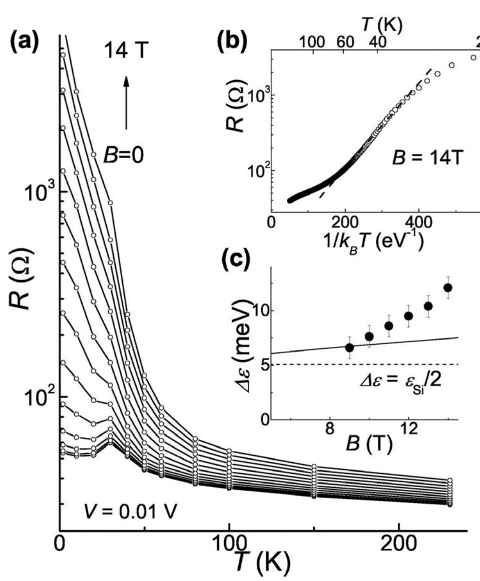

FIG. 5. (a) T dependence of R in $\mathbf{B}_\perp$ up to 14 T (V=0.01 V). (b) Dependence of R on $(k_BT)^{-1}$ at B=14 T. The line is an exponential fit to the data. (c) Measured B dependence of the activation energy $\Delta\varepsilon$. The continuous line is the calculated B dependence of $\Delta\varepsilon$ according to an hydrogenic model that uses as input parameters the electron effective mass and the binding energy of a Si donor in $GaAs_{1-x}N_x$. The dashed line is the calculated value of $\Delta\varepsilon$ at B=0.

In previous studies, we focused on the magnetic field dependence of the onset of the NDC with B up to 23 T and T=4.2 K.[20,21] Here, we turn our attention to the magnetoresistance at biases below those corresponding to the NDC region and to the MPR in the two orientations of $\mathbf{B}$ up to fields of 47 T. Since magnetophonon resonances are a manifestation of electrons undergoing cyclotron motion, they provide direct evidence that the extended conduction band states of $GaAs_{1-x}N_x$ contribute to the measured electrical conduction. We also note that the measured MPR at low T (<60 K) is a hot electron effect: Under the large applied electric fields (>100 V/cm) used in our experiment, electrons acquire sufficient energy to emit an LO phonon.[16] In the $\mathbf{B}_\perp$ orientation, we observed that the minima in $-d^2R/dB^2$ (maxima in the current) occur when a multiple of the Landau level spacing, $\hbar\omega_c$, matches the energy of LO phonons, $\hbar\omega_{LO}$, i.e., when $\omega_{LO}=i\omega_c$, where i is an integer. At this magnetophonon resonance condition, the rate of inelastic scattering by LO phonons is resonantly enhanced, enabling current flow along the electric field direction.[16] The behavior of the magnetoconductivity in these samples is different from that in conventional Hall bar epilayers. In the $\mathbf{B}_\perp$ configuration, no significant Hall voltage is generated in the thin $GaAs_{1-x}N_x$ layer of our mesa diodes. In fact, since the diameter (20 μm) of the mesa is considerably larger than the thickness (0.6 μm) of the $GaAs_{1-x}N_x$ layer, the Hall electric field is effectively short circuited by the highly conducting n^+-GaAs cladding layers [the n^+-GaAs/Ga(AsN) interfaces are equipotential surfaces to a good approximation]. Therefore, the measured transverse magnetoresistance is proportional to the inverse of the longitudinal conductivity, i.e., $R\sim\sigma_{xx}^{-1}$, rather than $R\sim\sigma_{xx}/\sigma_{xy}^2$ as is the case for Hall bars in the high magnetic field limit.[22] For the $\mathbf{B}_\parallel$ geometry, we observe maxima rather than minima in the plot of $-d^2R/dB^2$ vs B [Fig. 3(b)]. In this configuration, the cooling of hot electrons by LO phonon emission reduces the current flow along the direction of $\mathbf{E}$. Also, note the extended shoulder at around 27 T [marked by an asterisk in Fig. 3(b)] for the $\mathbf{B}_\parallel$ data, which we attribute to a subtle MPR process involving competition between different types of inter-Landau level scattering transitions with two phonons.[16]

As shown in the inset of Fig. 3(a), the positions in $1/B$ of the maxima or minima of $-d^2R/dB^2$ plotted as a function of the integer i fall on a straight line which extrapolates to i =0 at $1/B$=0. From the linear fit to the data by the relation $\omega_{LO}=i\omega_c$, we obtain the fundamental field B_f=40±3 T at which the cyclotron energy is equal to $\hbar\omega_{LO}$ and a corresponding period $B_f^{-1}=\Delta(1/B)=0.025\pm0.002$ T^{-1} in the maxima and/or minima of $-d^2R/dB^2$. Using the value of Δ and $\hbar\omega_{LO}$=36.7 meV, we obtain an electron cyclotron mass

$m_e^* = e/\omega_{LO}\Delta = (0.13 \pm 0.01)m_e$, where m_e is the electron mass in vacuum. This is in quite good agreement with values of m_e^* obtained from independent optical experiments on other samples with the same N content ($m_e^* = 0.11m_e - 0.13m_e$).[6]

The fundamental MPR field B_f and the value of m_e^* for our $GaAs_{1-x}N_x$ samples are significantly larger than those obtained from our control sample,[22,23] namely, an all-GaAs n^+-n-n^+ mesa diode structure for which $B_f = 23$ T and $m_e^* = 0.07m_e$. These values for our control sample are similar to those obtained from previous measurements on high mobility planar Hall-bar epilayers of n-GaAs in the Ohmic regime.[24] Under non-Ohmic conditions at low temperatures the n-GaAs epilayers also revealed a second MPR series of peaks with a B_f value of 18 T arising from LO phonon emission accompanied by electron capture on donor ground state levels. This donor-associated MPR effect is described by the condition $\hbar\omega_{LO} = i\hbar\omega_c - \varepsilon_d(B)$, where $\varepsilon_d(B)$ is the B-dependent donor binding energy.[25,26] In our sample, we observe no indications of this second MPR series over a wide range of temperatures and of applied electric fields from the low-field Ohmic regime to up to fields of $E = 1.5$ kV/cm. This field is about 100 times larger than those used in earlier measurements of non-Ohmic MPR in planar epitaxial layers.[24,26] We attribute the absence of the second series to the high Si-donor doping level (1×10^{17} cm^{-3}) in our sample. The consequent broadening of the impurity level would make it difficult to resolve the donor-associated MPR series from the $\hbar\omega_{LO} = i\hbar\omega_c$ MPR series.

As shown in Fig. 4, the amplitude of the magnetophonon resonances decreases with increasing T. The width of the MPR resonances is weakly affected by temperature up to $T \sim 20$ K above which it tends to increase due to the increasing broadening of the LLs. We find that the oscillatory part of R is well described by the expression $\Delta R = \pm R(0)\exp(-2\pi\Gamma/\hbar\omega_c)\cos(2\pi\omega_{LO}/\omega_c)$,[27] where the positive (negative) sign refers to the perpendicular (parallel) orientation and $\Gamma = 12 \pm 1$ meV is the energy broadening of the LLs at $T = 4.2$ K. This value of Γ is larger than that measured for MPR in the Ohmic regime of high-mobility n-GaAs ($\Gamma < 4$ meV) (Ref. 24) and is consistent with the strong electron scattering by the single N atoms and N clusters in the $GaAs_{1-x}N_x$ alloy.[10,11,14,15]

In the $\mathbf{B}_\parallel$ orientation, the amplitude of the MPR oscillations is weakly affected by the applied bias and the oscillations are clearly observed at high B [Fig. 3(b)]. In contrast, in the $\mathbf{B}_\perp$ geometry, the oscillations dampen out and disappear completely at low voltages or high B (>25 T). In the Sec. III C, we consider how, under these conditions, the magnetic field induces freeze-out of electrons onto localized states and leads to a transition from extended state band type conduction to hopping type conduction. MPR oscillations can only be observed when free electrons dominate the conductivity, a condition which is not satisfied at low bias voltages and/or high $\mathbf{B}_\perp$ and low T.

C. Magnetic field induced “freeze-out” of electrons

We next consider the large magnetoresistance observed at low bias ($V \sim 0.01$ V) and low T (<100 K) (Fig. 2). Under these conditions, the magnetoresistance is largely governed by the presence of localized electron states close to the conduction band edge. In $GaAs_{1-x}N_x$, localized electronic levels associated with single N atoms and N aggregates, such as N-N pairs and higher-order clusters, admix with the delocalized band states of GaAs and gives rise to extended and localized states below and above the conduction band minimum.[8,9] The localized energy levels associated with N and the Si-donor dopant atoms in the $GaAs_{1-x}N_x$ layer can bind electrons at low temperatures ($T < 20$ K), thus leading to charge transport via thermally activated hopping between localized states. Hopping conduction is highly sensitive to magnetic field, which tends to compress the bound electronic wave function and increase the magnetoresistance due to a smaller overlap of the wave function tails between adjacent localized states below the band edge. Since electrons hop preferentially along the direction of $\mathbf{B}$ in which the magnetocompression of the electron wave function is weaker, the hopping magnetoresistance for $\mathbf{E}$ parallel to $\mathbf{B}$ is smaller than for the $\mathbf{B}_\perp$ case.[28] For the $\mathbf{B}_\perp$ configuration, we find that $R(B)/R(0) \sim \exp(B/B_0)$, with $B_0 = 3 \pm 1$ T at low bias ($V < 0.05$ V) and $T = 4.2$ K. According to a simple model, $B_0 = 4n_h^{2/3}\hbar/e$, where n_h is the density of localized states corresponding to a characteristic hopping length $l = n_h^{-1/3}$.[28] The value of $B_0 = 3 \pm 1$ T gives $l = 31 \pm 5$ nm corresponding to $n_h = (4 \pm 2) \times 10^{16}$ cm^{-3}, which is close to the nominal doping density of Si donors (10^{17} cm^{-3}) in the $GaAs_{1-x}N_x$ layer. This suggests that the localized states between which the electrons are hopping at low temperatures are associated with shallow hydrogenic Si donors rather than minima in the disorder potential due to the high concentration of N atoms ($\sim 2 \times 10^{19}$ cm^{-3} for $x = 0.1\%$).

At low temperatures ($T = 4.2$ K), increasing the applied bias above a threshold value leads to a rapid increase of current and decrease of magnetoresistance which we attribute to ionization of electrons out of the localized states [see Fig. 1(c)]. Here, we focus on the low bias magnetoresistance ($V < 0.05$ V) and its T dependence. Whereas at low T (2–30 K) and $B > 8$ T, the transverse magnetoresistance has an exponential-like dependence on B characteristic of hopping conduction, for high T (>100 K), it has a quadratic B dependence (Fig. 2), which is consistent with a regime of conduction through extended band states. We therefore focus on an intermediate temperature range, i.e., $T = 30$–100 K, in which the temperature dependence of the magnetoresistance is mainly determined by the rapid increase in free electron concentration due to thermal excitation into the conduction band of electrons “frozen” onto the Si donors in the presence of a high B.

As shown in Figs. 5(a) and 5(b), in this temperature range ($T = 30$–100 K), the magnetoresistance at high ($B > 8$ T) approximates to an exponential T dependence, i.e., $R(T)/R(0) \sim \exp(\Delta\varepsilon/k_BT)$, where $\Delta\varepsilon$ is a characteristic activation energy into the conduction band. Note that in the low temperature range ($T < 30$ K), the T dependence of R is weaker, consistent with thermally activated hopping between localized states.[28] We find that the value of $\Delta\varepsilon$ increases from 7 to 12 meV for B increasing from 9 to 14 T [Fig. 5(c)]. An increase in the activation energy with B has been observed previously in other semiconductor materials and attributed to magnetic freeze-out of conduction electrons onto donor impurity states due to the B induced increase of the donor binding energy.[28–31]

For our n-doped $GaAs_{1-x}N_x$, at low B, $\Delta\varepsilon$ tends to approach a value of about 5 meV, which is consistent with thermal activation of electrons out of Si-donor states into the conduction band, as the following argument shows. To estimate the value of $\Delta\varepsilon$, we use a hydrogenic model for Si donors in $GaAs_{1-x}N_x$. For our measured value of $m_e^*=(0.13\pm 0.01)m_e$ in $GaAs_{1-x}N_x$, this gives a donor binding energy $\varepsilon_{Si}=R_y(m_e^*/m_e)\kappa_r^{-2}=10.2$ meV and a Bohr radius $a=\kappa_r(m_e/m_e^*)a_0=5.3$ nm, where $\kappa_r=13.2$ is the relative permittivity, $R_y=1$ Ry$=13.6$ eV and $a_0=0.05$ nm is the Bohr radius of the hydrogen atom. Note that our estimated value of $\varepsilon_{Si}=10.2$ meV is significantly larger than that obtained for GaAs ($m_e^*=0.07m_e$, $\varepsilon_{Si}=5.5$ meV). Due to the high Si doping, we can assume that our $GaAs_{1-x}N_x$ layer is uncompensated and that the chemical potential is midway between the donor level and the band edge. Thus $\Delta\varepsilon=\varepsilon_{Si}/2=5.1$ meV, which is close to the measured values of $\Delta\varepsilon$ at low B [Fig. 5(c)]. Our measurements of the N-induced enhancement of m_e^* and of ε_{Si} and the corresponding decrease of the electron Bohr radius a are clear manifestations of the strong effect of N on the electronic properties of GaAs. Although a N-induced increase of ε_{Si} was predicted in previous work,[17] to our knowledge, it has not been observed previously in experiments.

As shown in Fig. 5(c), the B dependence of $\Delta\varepsilon(=\varepsilon_{Si}/2)$ deduced from our analysis is different from that calculated using a simple hydrogenic-effective mass model[32] that uses as input parameters the electron effective mass ($m_e^*=0.13m_e$) and the zero field binding energy ($\varepsilon_{Si}=10.2$ meV) of a Si donor in $GaAs_{1-x}N_x$. Our measured value of $\Delta\varepsilon$ increases with B more strongly than the calculated one. This discrepancy may be due to the strong effect of B on the nature, bandlike or impuritylike, of the Si-related states. In our highly Si-doped $GaAs_{1-x}N_x$ layer, at $B=0$, the donor wave functions tend to overlap. The value of $a=5.3$ nm at $B=0$ gives a critical value of the Si concentration $n\approx 1.3\times 10^{17}$ cm^{-3} for the metal-insulator transition (MIT) ($na^3\approx 0.02$), which is close to the nominal Si doping of our sample (1×10^{17} cm^{-3}). An increasing magnetic field increases the binding energy ε_{Si} of isolated Si donors and also compresses the electronic wave function, thus increasing the magnetoresistance due to the decreasing overlap of the wave function tails between adjacent localized states.[29–31] According to the hydrogenic model,[32] when B is increased from 0 to 14 T, the compression of the donor wave function reduces the effective Bohr radius from 5.3 to 3.7 nm, which corresponds to $na^3=0.005$, well below the critical value $na^3\approx 0.02$ for the MIT. It therefore seems likely that at high B, the T dependence of the magnetoresistance is also influenced by the B dependence of the overlap donor wave functions.

The effect of high magnetic fields on the activation energy into the conduction band and the spatial overlap between the localized states are clearly quite complex, especially for the case when the doping concentration is close to the MIT and when the effect of the N-induced disorder also needs to be considered. Further experiments involving a range of doping concentrations above and below the MIT coupled with a quantitative theoretical model are probably needed to provide a complete picture of the interplay of temperature, magnetic field, and applied bias in the freeze-out regime of this material system.

IV. CONCLUSIONS

Previous studies of magnetotransport properties of the dilute nitride alloy $GaAs_{1-x}N_x$ and the observation of quantum confinement effects in this system have been hindered by the difficulty of controlling the electronic properties and quality of this interesting semiconductor material. In this paper, we have focused on the electronic properties of structures with low x ($\sim 0.1\%$) over a wide range of temperature, magnetic field, and electric field. The value of the electron mobility of these samples ($\mu\sim 0.2$ m^2 V^{-1} s^{-1}) and the large quantizing magnetic field used in our experiments have allowed us to achieve values of $\mu B\gg 1$, which are sufficient to observe clear Landau level quantization and strong magnetophonon resonance effects. The MPR data combined with the observation of a magnetic field induced freeze-out of electrons bound to Si donors at low temperature has revealed the N-induced enhancement of the electron effective mass and of the binding energy of conduction electrons to Si donors in $GaAs_{1-x}N_x$.

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