Electron-phonon interaction in disordered semiconductors

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We have presented a detailed experimental investigation of the effects of disorder on the electron-phonon interaction in semiconducting InN system. Both the temperature (T) and disorder (electron mean free path l) dependences of the electron-phonon scattering time $\tau_{e\text{-}ph}$ have been determined from the weak localization analysis. It is found that $\tau_{e\text{-}ph}^{-1}$ exhibits a tendency to change gradually from the characteristic dependence $\tau_{e\text{-}ph}^{-1} \propto T^3 l^0$ in the pure limit to the form of $T^2 l^{-1}$ as the films become disordered. Our observation gives clear evidence for the substantial enhancement of the electron-phonon coupling in semiconductor structures due to elastic electron scattering. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2890055]

Weak localization (WL), a unique phenomenon in disordered systems, has attracted great attention since it was first theoretically predicted and experimentally demonstrated in 1979.[1] The WL magnetoconductivity is a powerful tool for studying relaxation mechanisms of conduction electrons. One focus of the phase-relaxation investigations is the disorder-induced modification of the electron-phonon (e-ph) interaction, which is a quantity that contributes to the development of mesoscopic devices.[2] Most of the experiments with ordinary metals show suppression of the e-ph interaction due to disorder, known as the Pippard ineffectiveness condition.[3] In this case, the e-ph scattering rate ($\tau_{e\text{-}ph}^{-1}$) modifies from T^3 dependence in the clean limit ($q_T l \gg 1$, q_T is the wave vector of a thermal phonon, and l the electron mean free path) to $\tau_{e\text{-}ph}^{-1} \propto T^4 l$ in the presence of strong disorder (dirty limit, $q_T l \ll 1$). In contrast, metallic alloys commonly demonstrate the disorder-enhanced relaxation with T^2 dependence of $\tau_{e\text{-}ph}^{-1}$.[4] Since in alloys different atoms vibrate in different ways, the breakdown of disorder-suppressed relaxation has been explained by the fact that even small difference in vibration of electron scatterers (impurities, defects, and boundaries) and host atoms changes drastically the interference of scattering mechanisms and results in enhancement of the e-ph interaction in the dirty limit.[5]

Until now, there is no any systematic experimental investigation of the disorder-induced modification of e-ph relaxation in semiconductors. The e-ph interaction has different origins in metals and semiconductors.[6] In metals, the deformation potential (DP) is associated with electron-gas compressibility, while in semiconductors, this contribution is negligible due to the typically small carrier concentration. The DP in semiconductors results mainly from a shift of the conduction band edge under the deformation, while in metals this contribution is small because of strong screening.[7] Therefore, the theories developed for metals[3] and alloys[5] are inapplicable to disordered semiconductors. Sergeev *et al.*[7] have recently developed a theory predicting the modification of the relaxation rate from $T^3 l^0$ in the clean limit to $T^2 l^{-1}$ in the dirty extreme for bulk semiconductors, with the disorder-induced enhancement due to elastic electron scattering.

As a promising semiconductor among group III-nitride compounds, indium nitride (InN) has recently received intensive research interests. The easy realization of n-type InN thin films with very high electron concentrations[8] provides the possibility to form a disordered semiconducting system. The conduction electrons in InN possess large mean free path, which further guarantees that the electronic system falls into a wide disordered regime. In this letter, we have presented a detailed study of the dephasing times in a series of InN films with $q_T l$ from 0.14 to 15.90. Our experimental results are in excellent agreement with the recent theoretical prediction.[7]

The serial semiconducting InN thin films (with thickness from 1.241 to 2.130 μm) with varying disorder were grown on (0001) α-Al_2O_3 substrates by reactive radio frequency magnetron sputtering at the temperature from 100 to 500 °C. During the deposition, we maintained the sputtering power of 100 W, sputtering pressure of 10 mTorr, gas flow of 3 SCCM, and deposition time of 60 min. Both the x-ray diffraction and Raman scattering measurements demonstrate that the c axis of InN with a wurtzite structure is perpendicular to the substrate surface of (0001) α-Al_2O_3.[9] Magnetoconductivity was measured within a van der Pauw configuration under an Oxford Instruments superconductive magnet, where the magnetic field B parallels the sample c axis and the measured temperature can be down to 4.0 K. Raman scattering was performed on a Jobin Yvon LabRAM HR 800 UV micro-Raman spectrometer at room temperature using 514.5 nm line from an Ar^+ laser.

We start with the analysis of the product of q_T and l in the studied InN thin films, since the disorder degree of a system in the frame of WL theory is determined by the values of $q_T l$. These two parameters are defined[4] by $q_T = k_B T/\hbar v_s$ and $l = 3\pi^2\hbar/k_F^2 e^2 \rho_0$, respectively, where v_s is the average sound velocity, ρ_0 the resistivity, and $k_F = (3\pi^2 n_e)^{1/3}$ the Fermi wave number. With the resistivity ρ_0 and electron density n_e determined by Hall measurements at 10 K, we could obtain $q_T l \approx (0.04 \sim 0.53)T$ (T is in kelvin) by taking $v_s \approx 2.88 \times 10^3$ m/s for InN.[10] Figure 1(a) presents the temperature dependent values of product $q_T l$ for the four InN thin films. It is clear that the serial samples fall in a wide disordered regime ($q_T l$ from 0.14 to 15.90) between the clean ($q_T l \gg 1$) and dirty ($q_T l \ll 1$) limits in the temperature range of our experiment. From Fig. 1(a), a numerical decrease in

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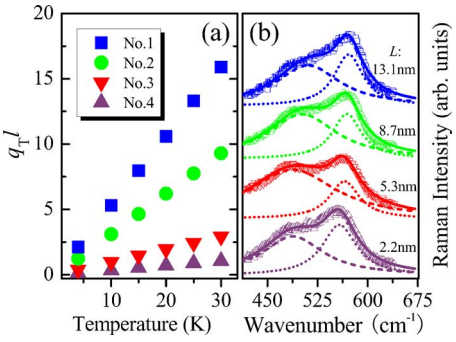

FIG. 1. (Color online) (a) Values of $q_T l$ in the four InN thin film samples at different temperatures, (b) room-temperature Raman spectra (scatters) of the four InN thin film samples. The spectra have been fitted by the combination (solid curves) of the SCM (dotted curves) and Lorentzian (dashed curves).

$q_T l$ from sample Nos. 1–4 can be observed, indicating an enhancement of disorder. We also find that the disorder degree becomes weaker with increasing temperature for all samples, which can be attributed to the strengthened lattice vibration at higher T.

Another evidence for the degree of disorder in the InN system could be shown by the correlation length L extracted from quantitative calculation of the Raman line shape with a spatial correlation model (SCM).[11] The SCM assumes that the phonons are propagating freely in a region of length L and are confined in that region. Beyond this length L, they get scattered from the crystal imperfections. Figure 1(b) shows the Raman spectra of the four InN samples, together with the theoretical results for the A_1 [longitudinal optical (LO)] phonon mode. A good fitting can be achieved by the SCM with an additional Lorentzian in the low frequency side due to the disorder-activated zone edge LO phonons.[12] The decrease of L indicates the enhancement of disorder, which coincides well with the observation in Fig. 1(a).

According to the WL theory, an anomalous magnetoconductivity $\sigma(B)$ is expected to be observed at low temperatures and weak magnetic fields. Figure 2 displays the typical experimental results of the normalized magnetoconductivity variation $\Delta\sigma(B)/\sigma(0)$ (circles) for InN sample No. 3 at different temperatures (4–30 K) in the magnetic field region of 0–2 T. It is clear that, at low B, $\Delta\sigma(B)/\sigma(0)$ is negative at all experimental temperatures, while it increases with B and becomes positive. Such a behavior of magnetoconductivity demonstrates the competition between spin-orbit scattering and inelastic scattering in InN films.[13] We have further found

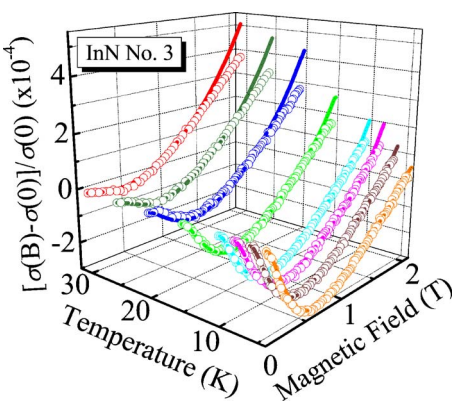

FIG. 2. (Color online) Quantum corrections to the conductivity of InN sample No. 3 vs perpendicular magnetic field at different temperatures.

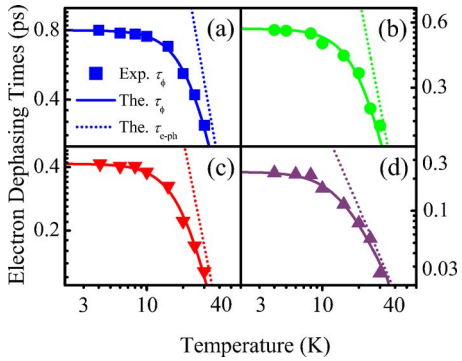

FIG. 3. (Color online) Temperature dependence of the relaxation times for InN samples (a) No. 1, (b) No. 2, (c) No. 3, and (d) No. 4 extracted from the experimental magnetoconductivity in Fig. 2. The solid curves are the theoretical fitting of τ_ϕ, while the dotted ones for $\tau_{e\text{-}ph}$.

that the magnitude of the magnetoconductivity decreases with increasing temperature. This temperature dependence could be attributed to the phase incoherence of electron wave functions caused by stronger e-ph inelastic scattering at higher T.

To describe quantitatively the temperature and magnetic field dependences of the magnetoconductivity, we have employed the well-known expressions for quantum corrections $\Delta\sigma(B,T)$ associated with the WL and EEI effects in three-dimensional (3D) systems. It should be noted that the 3D conditions are fulfilled for the studied InN thin films, since their thicknesses are much larger than the correlation lengths (or average grain sizes) L derived in Fig. 1(b). The magnetoconductivity correction due to the WL effect is given by Refs. 13 and 14.

Both the Zeeman spin splitting and orbital effects contribute to the electron-electron interaction (EEI) term of the magnetoconductivity. The orbital correction has been deduced by Isawa and Fukuyama,[15] the contribution of which is found to be considerably small in InN at the studied temperature and magnetic field. The main contribution from the Zeeman splitting is described by[1]

$$\Delta\sigma_{\mathrm{EEI}}(B) = -F_\sigma(e^2/4\pi^2\hbar)(k_BT/2\hbar D)^{1/2}G(gB\mu_B/k_BT), \quad (1)$$

with F_σ the electron screening constant, D the diffusion constant, and $g=2$ the Lande factor. Under the condition of $gB\mu_B/k_BT \ll 1$ that is satisfied in the present experiment, the function G can be approximated as $G(gB\mu_B/k_BT) = 0.329(gB\mu_B/k_BT)^{3/2}$.[16]

The solid curves in Fig. 2 are the calculated results of $\Delta\sigma(B)/\sigma(0)$. As expected, the 3D WL theory can well reproduce the experimental magnetoconductivity, except for the high temperature and strong magnetic field cases, where the WL theory gradually becomes invalid due to the increasing importance of classical magnetoconductivity. Figure 3 displays the extracted electron dephasing time τ_ϕ (scatters) as a function of T for the four InN thin films. It is clear that the dephasing time τ_ϕ exhibits an increasing tendency with the decreasing temperature and reaches saturation near zero temperature. This temperature dependent behavior has been attributed to the mechanism, which believes that the dangling bonds in the vicinity of grain boundaries act as the two-level centers in the highly degenerated semiconductor.[17]

It has been established that the e-ph scattering is the dominant inelastic process[4] in 3D materials, such as the present InN films. We should also take into account the zero-

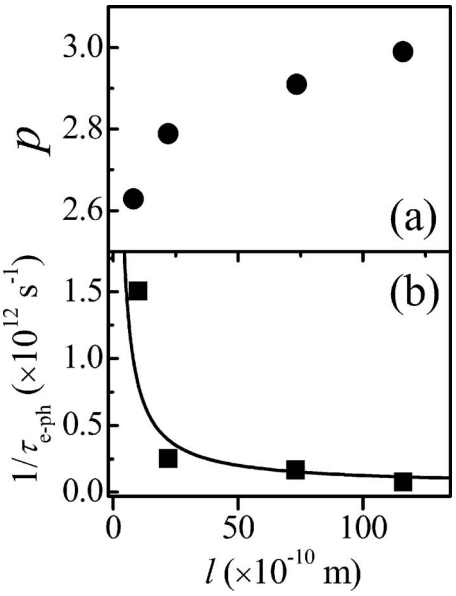

FIG. 4. (a) Values of p as a function of electron mean free path l, (b) electron-phonon scattering rate $1/\tau_{e\text{-}ph}$ (10 K) as a function of electron mean free path l for the four InN samples.

temperature saturation behavior in analyzing the temperature dependence of dephasing time τ_ϕ. As a result, the dephasing time τ_ϕ can be described by

$$1/\tau_\phi(T) \approx 1/\tau_0 + 1/\tau_{e\text{-}ph}(T) \approx 1/\tau_0 + A_{e\text{-}ph}T^p, \quad (2)$$

where τ_0 is the saturation time, $A_{e\text{-}ph}$ is the strength of e-ph coupling, and p is the exponent of temperature for the e-ph scattering rate $\tau_{e\text{-}ph}^{-1}$. As shown in Fig. 3, Eq. (2) can well explain the experimental results of τ_ϕ, which further reveals the temperature dependences of $\tau_{e\text{-}ph}^{-1}$ (dotted curves).

Figure 4 presents (a) the extracted exponent of temperature p and (b) the e-ph scattering rate $\tau_{e\text{-}ph}^{-1}$ for a certain temperature ($T=10$ K) as a function of electron mean free path l. It is clear that, in the relatively ordered samples ($q_T l > 1$), the value of p approximates to 3.0 and $\tau_{e\text{-}ph}^{-1}$ depends weakly on l. With the increase of disorder, p decreases (and inclines to 2.0 in the dirty limit) while $\tau_{e\text{-}ph}^{-1}$ increases dramatically in the region $q_T l < 1$. The solid curve in Fig. 4(b) is the fitting $\tau_{e\text{-}ph}^{-1}$ with l^{-1}. This observation suggests that the e-ph scattering rate $\tau_{e\text{-}ph}^{-1}$ can be characterized by the dependence $\tau_{e\text{-}ph}^{-1} \propto T^3 l^0$ in the pure case ($q_T l > 1$) and inclines to obey the law of $T^2 l^{-1}$ as the films become disordered. It is clear that the obtained results are in excellent agreement with the theory recently developed for bulk semiconductors in weak screening (within the measured temperature of 4–30 K).[7] In disordered metallic systems, however, Belevtsev *et al.*[18] have reported an occurrence of disorder-suppressed relaxation in the pure-dirty transition of gold films, while Lin *et al.*[19] have found that $\tau_{e\text{-}ph}^{-1}$ exhibited constant temperature dependence in the form of $\tau_{e\text{-}ph}^{-1} \propto T^{2.4\pm0.2}$ without notable disorder influence in Sb films.

In the clean limit, both our observation for semiconductors and previous reports on metals agree that the e-ph scattering rate $\tau_{e\text{-}ph}^{-1}$ depends on the temperature in the form of $\tau_{e\text{-}ph}^{-1} \propto T^p$. Although p is theoretically predicted to be equal to 3 in the region of $q_T l \gg 1$, the experimental results would be affected by many factors and usually deviate from the expected value (i.e., the specific value of p varies for different disordered systems). The quadratic temperature dependence observed in the gold films[18] was attributed to the existence of Love's wave in the interface of the gold-sapphire system, which caused the same effect as reducing dimension; while the noninteger value of p extracted in Ref. 19 might be resulted from the characteristic microscopic structure in 3D disordered Sb films. The near cubic temperature dependence in the present experiment suggests normal e-ph scattering mechanism in semiconducting InN.

However, with the increase of disorder toward the dirty limit ($q_T l < 1$), the observed modifications of $\tau_{e\text{-}ph}^{-1}$ due to disorder in semiconducting InN films are quite different from the results in disordered metallic systems. In Sb films, no remarkable disorder effect on $\tau_{e\text{-}ph}^{-1}$ was found in the region which was strictly restricted near $q_T l = 1$.[19] It is quite possible that the disorder dependence within such a narrow disordered region is too weak to be observed. The disorder-suppression relaxation in gold films[18] within a wide disorder range is completely contrary to our results in semiconducting InN films. Nevertheless, this contradiction can be well understood on the basis of different natures of the DP in semiconductors and metals.[7] As we know, the electron relaxation is determined by e-ph scattering via the DP, which depends weakly on the electron momentum with the tensor usually approximated by a constant in semiconductors. In contrast, the Fermi surface average of the DP equals to zero in metals. As a result, the relaxation rate in semiconductors is enhanced due to the elastic electron scattering from impurities and defects,[7] while the destructive interference of scattering mechanisms in metals leads to the Pippard ineffectiveness condition exhibiting the suppression of the e-ph relaxation.[3]

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