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We report on the photoconductivity study of the individual infrared-absorbing indium nitride (InN) nanowires. Temperature-dependent dark conductivity measurement indicates the semiconducting transport behavior of these InN nanowires. An enhanced photosensitivity from 0.3 to 14 is observed by lowering the temperature from 300 to 10 K. A calculated ultrahigh photoconductive gain at around 8×10^7 at room temperature is obtained from the low-bandgap nitride nanowire under 808 nm excitation. © *2009 American Institute of Physics*. [doi:10.1063/1.3242023]

Indium nitride (InN) with the lowest direct bandgap ($\sim$0.6 eV) among III-nitride semiconductors has gained substantial attention due to its potential for the development of new-generation infrared (IR) optoelectronic devices. The low electron effective mass ($m^*\sim0.06m_e$) also enables InN to be a candidate material for high-speed electronics.[1,2] Recently, an intrinsic surface conduction due to the presence of resonant surface states in InN is also observed,[3] which inspires the interest in fundamental researches[4,5] and related applications such as terahertz emission,[6] ion sensing,[7] and field emission.[8]

Owing to these interesting bulk and surface nature of InN, a numbers of effort have also been extended to the electrical[9–14] and optical properties[15,16] of its nanowire (NW) with size-confined and quasi-one-dimensional (quasi-1D) nanostructure. Electronic transport[12–14] and IR photoluminescence (PL)[15,16] have been proven of being dominated or influenced by the electron accumulation layer on surface. However, so far, the study of photoconductivity (PC), which is the most crucial issue for the development of IR detectors using InN and its nanostructures, has hardly been investigated yet.[17] The extremely degenerate nature with high intrinsic carrier concentration could partially suppress the photoresponse in InN.[14] Here, we report on the efficient PC performance in the nonmetallic InN NWs upon 808 nm IR irradiation. The temperature-sensitive photosensitivity and very high photocurrent gain induced by long carrier lifetime are presented and discussed.

The InN NWs used for this study were grown at 480 °C by metalorganic chemical vapor deposition (MOCVD) using trimethylindium and ammonia (NH_3) source reagents and gold (Au) catalyst. The morphologies, structures, and long-axial orientations of the InN NWs grown in this way were characterized by field-emission scanning electron microscopy (FESEM) (JEOL 6700), transmission electron microscopy (TEM) (JEOL JEM-4000EX), and selected-area electron diffractometry (SAED), respectively. PL measurements were performed at 20 K using 532 nm Nd^+:YAG (YAG denotes yttrium aluminum garnet) laser as excitation source. The collected PL light was dispersed through a 0.5 m monochromator equipped with a 300 g/mm grating and was detected by an extended InGaAs detector. The temperature-dependent dark- and photo-current measurements of the InN NW devices were carried out on a cryogenic probe station (LakeShore Cryotronics model TTP4). A semiconductor characterization system (Keithley model 4200-SCS) was utilized to source the dc bias and measure the current. The 808 nm diode laser was used as the excitation source in the PC experiment.

Figure 1(a) depicts the FESEM image of the ensemble of the as-grown InN NWs. The average diameters (d) and lengths (l) are 20–80 nm and 8–12 μm, respectively. The single crystalline structure and the $\langle110\rangle$ long-axis orientation are confirmed by the TEM and its corresponding SAED pattern [Fig. 1(b)]. Figure 1(c) illustrates the PL spectrum of the as-grown InN NWs at the temperature of 20 K. Using

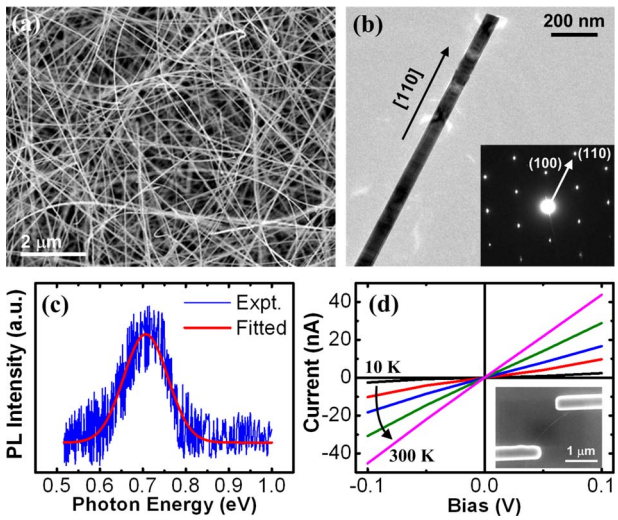

FIG. 1. (Color online) (a) The FESEM image of the ensemble of the as-grown InN NWs. (b) The TEM image and its corresponding SAED pattern (the inset) of a single InN NW. (c) A typical PL spectrum measured at 20 K of the ensemble of the as-grown InN NWs. (d) The selected i_d-V curves of a single InN NW device with diameter of 35 ± 5 nm measured at different temperature in vacuum. Inset in (d) shows the typical FESEM image of a single InN NW device with two Pt contacts fabricated by FIB deposition.

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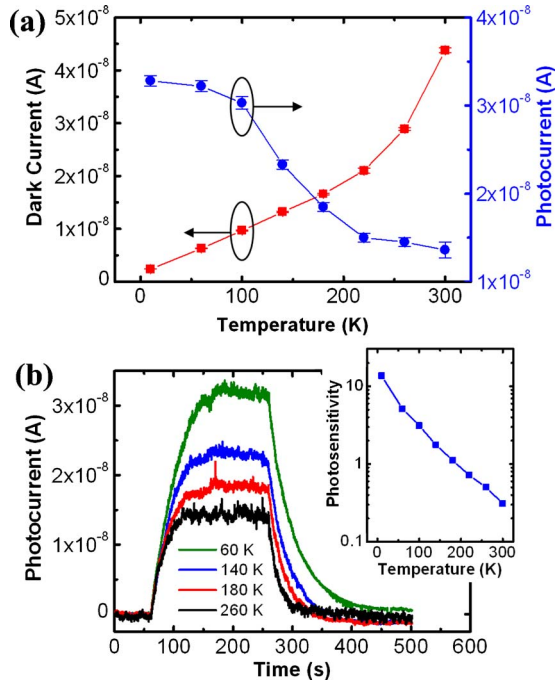

FIG. 2. (Color online) (a) The temperature-dependent dark and photocurrents of the single InN NW in the range of 10–300 K. (b) The selected photocurrent response to the 808 nm excitation of the single InN NW at different temperatures in vacuum. Inset in (b) shows the temperature-dependent photosensitivity of the single InN NW in the range of 10–300 K.

Gaussian fitting, the PL spectrum can be fitted with a single peak centering at ~0.707 eV and broadening of ~102 meV. This IR-emission peak position is also consistent with the band-to-band emission observed from the high-quality nanorods[15] and epitaxial films.[18]

Two-terminal single InN NW samples using platinum (Pt) metal contacts, as shown in the inset of Fig. 1(d), were fabricated by focused-ion-beam (FIB) deposition on the insulating SiN_x(500 nm)/Si substrates. Figure 1(d) illustrates the dark current (i_d) to bias (V) measurements at different temperatures (T) in vacuum for the NW with $d=35\pm5$ nm. The linear i_d-V curves in the temperature range of 10–300 K reveal good Ohmic contact property of this single wire device. Moreover, at a constant bias of 0.1 V, the i_d decreases over 1 decade as the temperature lowers from 300 to 10 K [Fig. 2(a)], indicating the semiconducting nature of the InN NW. The room-temperature conductivity estimated from the i_d-V measurement is around 10 Ω^{-1} cm^{-1}.

The PC of the single InN NW was characterized subsequently using the 808 nm excitation source. Figure 2(b) depicts the selected photocurrent (i_p) responses at the bias of 0.1 V at different temperatures in vacuum, in which the background i_d currents have been subtracted. The i_p value shows a continuous increase as the temperature lowers, which is opposite to the trend of i_d, as shown in Fig. 2(a). The effective reduction in thermal current and the enhancement of i_p response at low temperature both benefit the photosensitivity (S) to the IR detection of InN NWs. Photosensitivity, defined as the ratio of photocurrent to dark current, i.e., $S=i_p/i_d$, is the parameter electrically determining the signal-to-noise ratio for the operation of photodetectors. The inset in Fig. 2(b) depicts the increase in S over one order of magnitude from 0.3 to 14 in this investigated temperature range, indicating the good device performance for IR sensing. Since narrow-bandgap semiconductors frequently suffer from high thermal current, the preliminary sensitivity of InN NWs is already compatible with other photoconductor-type IR detectors based on 1D nanostructure, such as germanium (Ge) NW,[19] indium phosphide (InP) NW,[20] and carbon nanotube.[21]

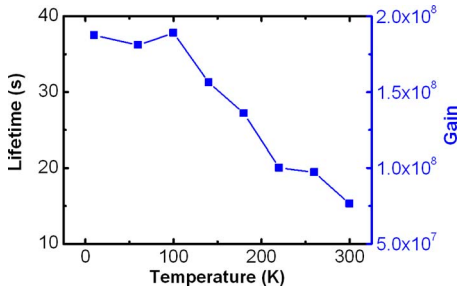

FIG. 3. (Color online) The temperature-dependent carrier lifetime and its corresponding photocurrent gain of the single InN NW in the range of 10–300 K in vacuum.

Upon fitting the rise times of i_p response curve in Fig. 2(b), the carrier lifetime (τ) at different temperatures can be obtained and plotted as shown in the inset of Fig. 3. It is noted that the very long τ of the order of tens of seconds is obtained in the InN NWs. The τ values show a 2.5 times increase from 15 to 38 s as the temperature decreases from 300 to 10 K. This result corroborated with the trend of i_p versus T [Fig. 2(a)] suggests that the i_p is dominated by the long τ in this nitride NW. Compared to normal photoconductors with τ in the time scales of microseconds to milliseconds, the τ of InN NWs in tens of seconds implies several decades higher i_p generation efficiency and could originate from a different mechanism. To investigate the transport property of photocarriers, the photocurrent gain (Γ), a factor determining the electronic transport and carrier collection efficiency during the PC process, is estimated. The physical meaning of Γ relates to the number of electrons circulating through the photoconductor per absorbed photon and per unit time. Accordingly, Γ is defined as[22,23]

$$\Gamma = \frac{\tau}{t}, \tag{1}$$

where t is the transit time of carrier between electrodes. Since $t=l/v$, where v, the carrier drift velocity, is the product of mobility (μ) and applied electric field (F), i.e., $v=\mu F$, Γ can be rewritten as[23]

$$\Gamma = \tau\mu\frac{F}{l}. \tag{2}$$

According to our field-effect measurement by directly applying gate voltage from the bottom of the single NW devices, the μ values of the InN NWs are around 2 ± 1 cm^2/V s. Thus, the Γ values are estimated as $(8\pm4)\times10^7$ at room temperature for $\tau=15$ s, $F=5\times10^2$ V/cm, and $l=2$ μm. Its temperature dependence is also illustrated in Fig. 3. So far, no Γ value has been defined from the InN system. As Γ value depends on the experimental parameters, comparison must be made in the same condition. However, overall, this value of InN NWs is several orders of magnitude higher than those ($\Gamma<10^4$) of different types of

high-efficiency photodetectors, such as thin film photoconductor,[24,25] NW phototransistor,[26] quantum dot photodetector.[27,28]

Recently, the ultrahigh-gain transport has also been observed in the wide-bandgap semiconducting NWs of GaN[29] and ZnO.[30] Soci *et al.* reported a maximal Γ value of 2×10^8 for a ZnO NW with the same l at 2 μm at higher F of 2.5×10^4 V/cm.[30] Under the same applied field, the Γ of the InN NWs can easily reach $(4\pm2)\times10^9$, which is even higher than that of ZnO NWs. Moreover, the GaN and ZnO NWs have two different high-gain (long lifetime) mechanisms. Photoconduction of GaN NW is dominated by the electron-hole spatial separation induced by strong surface band bending.[29,31] However, the oxide NWs usually follow a molecular sensitization mechanism similar to a hole-trapping effect.[30] InN with a well-known surface electron accumulation in nature is totally different from the electron depletion of surface in ordinary *n*-type semiconductors, such as GaN and ZnO systems. Further studies suggest that the photocurrent in InN NWs is sensitive to the oxygen environment (not shown here) and its PC could be surface dominant and follows a similar mechanism of molecular sensitization. The excitation of electron from surface state created by foreign oxygen molecule could give rise to a similar effect as interband excitation since the lifetime of photoelectron is also determined by the readsorption rate of oxygen.

In addition, the intrinsic types of unintentional doping or defects presented in this work are likely to be different from our previous reports[10] due to the different processes in producing these NWs. The MOCVD approach seems to favor the NWs with lower conductivity and semiconducting nature. The reason underneath the process-dependent electronic behavior is still not very clear. Usually, lower conductivity could imply higher crystalline quality, less donor defects, and compensation of acceptor defects in this intrinsic *n*-type semiconductor. The potential existence of acceptor states in the InN has been widely proposed for the explanation of different experimental observations including PL[18,32,33] and Hall measurements.[34] However, further studies are still required to clarify the origins of the semiconducting transport in the InN NWs.

In conclusion, the PC of the semiconducting InN NWs with ultrahigh photocurrent gain has been investigated. The photosensitivity for the IR illumination can be significantly enhanced at low temperature due to the reduction in thermal current and an increase in the photocurrent. The preliminary results demonstrate the potential application as an efficient IR sensing material using the InN nanostructure. The mechanism leading to the high-gain transport is still needed to be elaborated.

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[1]W. Walukiewicz, J. W. Ager III, K. M. Yu, Z. Liliental-Weber, J. Wu, S. X. Li, R. F. Jones, and J. D. Denlinger, J. Phys. D: Appl. Phys. **39**, R83 (2006).
[2]S. K. O'Leary, B. E. Foutz, M. S. Shur, and L. F. Eastman, Appl. Phys. Lett. **88**, 152113 (2006).
[3]I. Mahboob, T. D. Veal, C. F. McConville, H. Lu, and W. J. Schaff, Phys. Rev. Lett. **92**, 036804 (2004).
[4]L. Colakerol, T. D. Veal, H. K. Jeong, L. Plucinski, A. DeMasi, T. Learmonth, P. A. Glans, S. Wang, Y. Zhang, L. F. J. Piper, P. H. Jefferson, A. Fedorov, T. C. Chen, T. D. Moustakas, C. F. McConville, and K. E. Smith, Phys. Rev. Lett. **97**, 237601 (2006).
[5]S. Lazic, E. Gallardo, J. M. Calleja, F. Agulló-Rueda, J. Grandal, M. A. Sánchez-Garcia, E. Calleja, E. Luna, and A. Trampert, Phys. Rev. B **76**, 205319 (2007).
[6]V. Cimalla, B. Pradarutti, G. Matthäus, C. Brückner, S. Riehemann, G. Notni, S. Nolte, A. Tünnermann, V. Lebedev, and O. Ambacher, Phys. Status Solidi B **244**, 1829 (2007).
[7]Y. S. Lu, C. L. Ho, J. A. Yeh, H. W. Lin, and S. Gwo, Appl. Phys. Lett. **92**, 212102 (2008).
[8]K. R. Wang, S. J. Lin, L. W. Tu, M. Chen, Q. Y. Chen, T. H. Chen, M. L. Chen, H. W. Seo, N. H. Tai, S. C. Chang, I. Lo, D. P. Wang, and W. K. Chu, Appl. Phys. Lett. **92**, 123105 (2008).
[9]T. Tang, S. Han, W. Jin, X. Liu, C. Li, D. Zhang, C. Zhou, B. Chen, J. Han, and M. Meyyapan, J. Mater. Res. **19**, 423 (2004).
[10]C. Y. Chang, G. C. Chi, W. M. Wang, L. C. Chen, K. H. Chen, F. Ren, and S. J. Pearton, Appl. Phys. Lett. **87**, 093112 (2005).
[11]G. Cheng, E. Stern, D. Turner-Evans, and M. A. Reed, Appl. Phys. Lett. **87**, 253103 (2005).
[12]C. Y. Chang, G. C. Chi, W. M. Wang, L. C. Chen, K. H. Chen, F. Ren, and S. J. Pearton, J. Electron. Mater. **35**, 738 (2006).
[13]E. Calleja, J. Grandal, M. A. Sánchez-García, M. Niebelschütz, V. Cimalla, and O. Ambacher, Appl. Phys. Lett. **90**, 262110 (2007).
[14]R. Calarco and M. Marso, Appl. Phys. A: Mater. Sci. Process. **87**, 499 (2007).
[15]C. H. Shen, H. Y. Chen, H. W. Lin, S. Gwo, A. A. Klochikhin, and V. Yu. Davydov, Appl. Phys. Lett. **88**, 253104 (2006).
[16]T. Stoica, R. J. Meijers, R. Calarco, T. Richter, E. Sutter, and H. Luth, Nano Lett. **6**, 1541 (2006).
[17]S. Vaddiraju, A. Mohite, A. Chin, M. Meyyappan, G. Sumanasekera, B. W. Alphenaar, and M. K. Sunkara, Nano Lett. **5**, 1625 (2005).
[18]B. Arnaudov, T. Paskova, P. P. Paskov, B. Magnusson, E. Valcheva, B. Monemar, H. Lu, W. J. Schaff, H. Amano, and I. Akasaki, Phys. Rev. B **69**, 115216 (2004).
[19]B. Polyakov, B. Daly, J. Prikulis, V. Lisauskas, B. Vengalis, M. A. Morris, J. D. Holmes, and D. Erts, Adv. Mater. (Weinheim, Ger.) **18**, 1812 (2006).
[20]N. P. Kobayashi, V. J. Logeeswaran, M. Saif Islam, X. Li, J. Straznicky, S. Y. Wang, R. S. Williams, and Y. Chen, Appl. Phys. Lett. **91**, 113116 (2007).
[21]I. A. Levitsky and W. B. Euler, Appl. Phys. Lett. **83**, 1857 (2003).
[22]P. Bhattacharya, *Semiconductor Optoelectronic Devices* (Prentice-Hall, New Jersey, 1997).
[23]M. Razeghi and A. Rogalski, J. Appl. Phys. **79**, 7433 (1996).
[24]M. Asif Khan, J. N. Kuznia, D. T. Olson, J. M. Van Hove, M. Blasingame, and L. F. Reitz, Appl. Phys. Lett. **60**, 2917 (1992).
[25]M. Liao and Y. Koide, Appl. Phys. Lett. **89**, 113509 (2006).
[26]Y. H. Ahn and J. Park, Appl. Phys. Lett. **91**, 162102 (2007).
[27]G. Konstantatos, I. Howard, A. Fischer, S. Hoogland, J. Clifford, E. Klem, L. Levina, and E. H. Sargent, Nature (London) **442**, 180 (2006).
[28]G. Konstantatos, L. Levina, A. Fischer, and E. H. Sargent, Nano Lett. **8**, 1446 (2008).
[29]R. S. Chen, H. Y. Chen, C. Y. Lu, K. H. Chen, C. P. Chen, L. C. Chen, and Y. J. Yang, Appl. Phys. Lett. **91**, 223106 (2007).
[30]C. Soci, A. Zhang, B. Xiang, S. A. Dayeh, D. P. R. Aplin, J. Park, X. Y. Bao, Y. H. Lo, and D. Wang, Nano Lett. **7**, 1003 (2007).
[31]R. S. Chen, S. W. Wang, Z. H. Lan, J. T. H. Tsai, C. T. Wu, L. C. Chen, K. H. Chen, Y. S. Huang, and C. C. Chen, Small **4**, 925 (2008).
[32]A. A. Klochikhin, V. Yu. Davydov, V. V. Emtsev, A. V. Sakharov, V. A. Kapitonov, B. A. Andreev, H. Lu, and W. J. Schaff, Phys. Rev. B **71**, 195207 (2005).
[33]W. H. Chang, W. C. Ke, S. H. Yu, L. Lee, C. Y. Chen, W. C. Tsai, H. Lin, W. C. Chou, M. C. Lee, and W. K. Chen, J. Appl. Phys. **103**, 104306 (2008).
[34]D. C. Look, H. Lu, W. J. Schaff, J. Jasinski, and Z. Liliental-Weber, Appl. Phys. Lett. **80**, 258 (2002).