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Quasi-two-dimensional superconductivity in wurtzite-structured InN films

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C-axis oriented InN films with wurtzite structure were grown on sapphire (0001) substrate by MOCVD method. Superconductivity with transition onset temperature $T_{c,onset}$ around 3.5 K has been characterized by magnetotransport measurements in fields up to 9 Tesla for films with carrier concentration in the range of 1×10^{19} cm^{-3} to 7×10^{20} cm^{-3}. Among them, the film with a nitridation buffer layer has the highest zero-resistance temperature T_{c0} of 2 K. The normal-state magnetoresistance follows Kohler's rule $\Delta R/R \propto (H/R)^2$, indicating that there is a single species of charge carrier with single scattering time at all points on the Fermi surface. The extrapolated value of zero-temperature upper critical field $H_{c2}{}^{ab}(0)$ and $H_{c2}{}^{c}(0)$ is estimated to be 5900 G and 2800 G, respectively, giving rise to the anisotropy parameter γ about 2.1. The angular dependence of the upper critical field is in good agreement with the behavior predicted by Lawrence-Doniach model in the two-dimensional (2D) limit strongly suggesting that the InN film is a quasi-2D superconductor.

1 Introduction

Superconductivity in InN, a III-nitride semiconductor with a variety of optoelectronic applications, was first observed by Inushima *et al.* in 2000 [1]. Experimental studies have shown that neither micro-network of metal-In clusters nor intrinsic surface-electron accumulation layers are responsible for superconductivity [2–4]. The crystal structure of InN can be regarded as two-dimensional In-layer intercalated by N layers along *c*-axis. The Thomas-Fermi screening length of InN obtained from Shubnikov-de Haas (SdH) measurements is on the order of 100 Å [4], indicating the long-range Coulomb interaction between electrons becomes essential. For such a strongly correlated electron system with low dimensionality, it is generally believed that an anisotropic electronic structure with a strong electron-phonon interaction should exist and carriers near Fermi level often strongly couple with a lattice vibration, thereby leading to ordered phases at low temperatures. Despite of extensive investigations [5, 6], the electron-phonon interaction of InN is not yet well understood. Up to date, no consensus is emerged about the origin and underlying mechanism of superconductivity in InN. To shed light on a better understanding of superconducting properties of InN, magnetotransport measurements have been performed and the observed results strongly suggest that the InN film is a quasi-2D superconductor.

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2 Experimental details

InN films were grown with unintentional doping by an Aixtron 200/4RF-S metal-organic vapor phase epitaxy (MOVPE) system on sapphire (0001) substrate with various buffer layers. The details of growth conditions are reported elsewhere [7, 8]. X-ray diffraction patterns and Raman spectra show that the films investigated are *c*-axis oriented with a wurtzite structure. It should be mentioned that the as-deposited In-N film is always an *n*-type semiconductor with a decent amount of carrier concentration possibly arising from nitrogen vacancy, nitrogen antiside, and interstitial hydrogen as well. The films studied have mobility varying from 200 to 1200 cm^2/Vs and carrier concentration ranging from 1×10^{19} cm^{-3} to 7×10^{20} cm^{-3} determined from Hall measurements with the van der Pauw method. Magnetotransport properties were measured in fields up to 9 T by a conventional four-probe method.

3 Results and discussion

The InN films deposited on various buffer layers have superconducting transition onset temperature $T_{c,onset}$ around 3.4 K. Among them, the film with a nitridation buffer layer has the highest zero-resistance temperature T_{c0} of 2 K. All the representative figures displayed below are measurements on the InN film deposited on a nitridation buffer layer. The temperature dependence of the resistance for InN film with different fields applied in the *ab*-plane and along the *c*-axis is shown in Figs. 1(a) and (b). It is clear that there is a prominent anisotropy in the upper critical field parallel and perpendicular to the *ab*-plane. In addition, the temperature dependence of resistance in the superconducting state changes from convex to concave behavior as the magnetic field increases, indicating that the vortex dynamics of the InN film is distinctly different from that of cuprate superconductors. The observed broadening of resistive transition arising from thermally activated flux flow first proposed by Anderson is quantitatively expressed by $R(T,H) = R_0 exp(-E_a(H)/k_BT)$ [9]. The field dependence of the effective flux pinning energy E_a with field applied in the *ab*-plane and along the *c*-axis is illustrated in the insets of Figs. 1(a) and (b), respectively. It is interesting to note that both the E_a and T_c of the wurtzite-structured InN film are two orders of magnitude smaller than those of YBCO. More importantly, the effective flux pinning energy E_a linearly proportional to $ln(H^{-1})$ strongly suggests that the vortex line of InN is quasi-two-dimensional (2D) and disorder-induced quantum frustrations cause the quasi-2D vortex solid to melt into a quantum vortex liquid below a critical field [10]. This scenario is in excellent agreement with a mechanism proposed by Inushima where the occurrence of the superconductivity is related to the presence of In-In chains of finite length in the *ab*-plane [5].

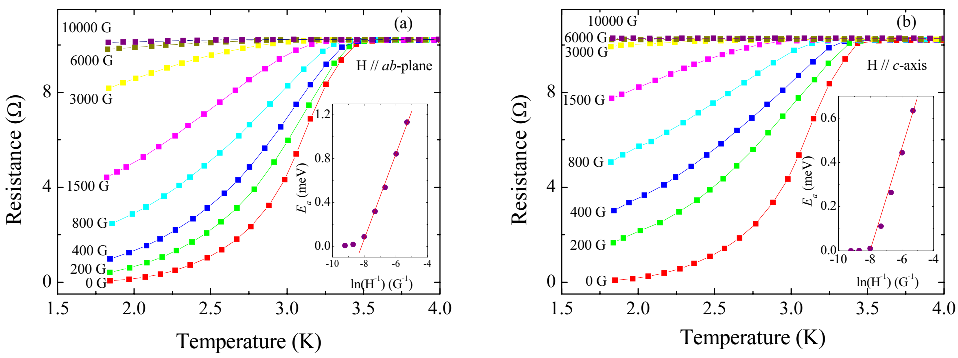

Fig. 1 Resistance as a function of temperature of InN film deposited on nitridation buffer layer with field in the *ab*-plane (a) and along the *c*-axis (b). The insets display the effective flux pinning energy E_a versus $ln(1/H)$ plots.

The magnetic phase diagram $H_{c2}(T)$ deduced from $R(H)$ at various temperatures and $R(T)$ at different fields is displayed in Fig. 2(a). The $H_{c2}(T)$ can be well-fitted with phenomenological relation $H_{c2}(0)$[1-

$(T/T_c)^2$]. The extrapolated value of $H_{c2}^{ab}(0)$ and $H_{c2}^{c}(0)$ is estimated to be 5900 G and 2800 G, respectively. It leads to the anisotropic parameter $\gamma = H_{c2}^{ab}/H_{c2}^{c}$ about 2.1. Furthermore, as shown in Fig. 2(b), the normal-state transverse magnetoresistance ratio $\Delta R/R$ at various temperatures scales with $(H/R)^2$ known as Kohler's rule. It indicates that there is a single species of charge carrier with single scattering time at all points on the Fermi surface [11].

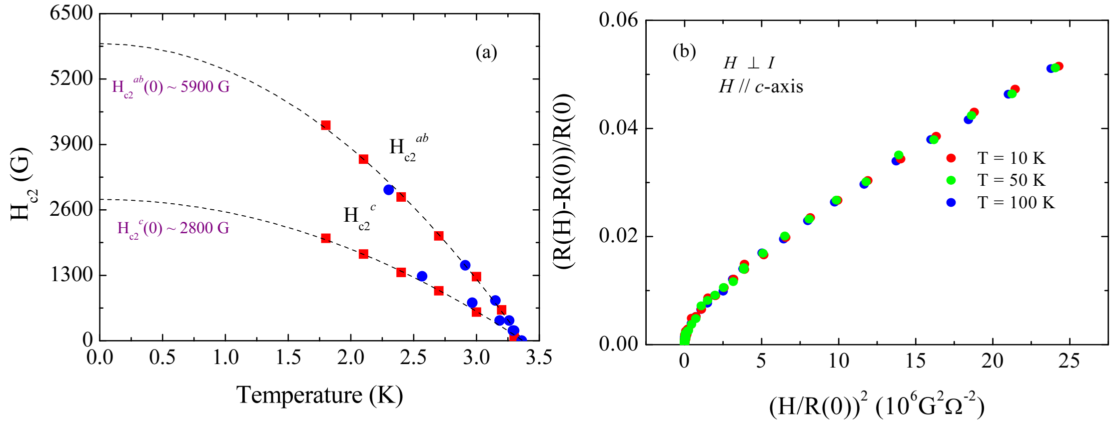

Fig. 2 (a) Upper critical field H_{c2} for fields perpendicular and parallel to the *ab*-plane as a function of temperature. (▪) and (•) were determined by $R(H)$ at various T and $R(T)$ at different H, respectively. (b) Normal-state transverse magnetoresistance ratio versus $(H/R(0))^2$ plot at various temperatures. It is interesting to note that all the data collapse onto a universal curve.

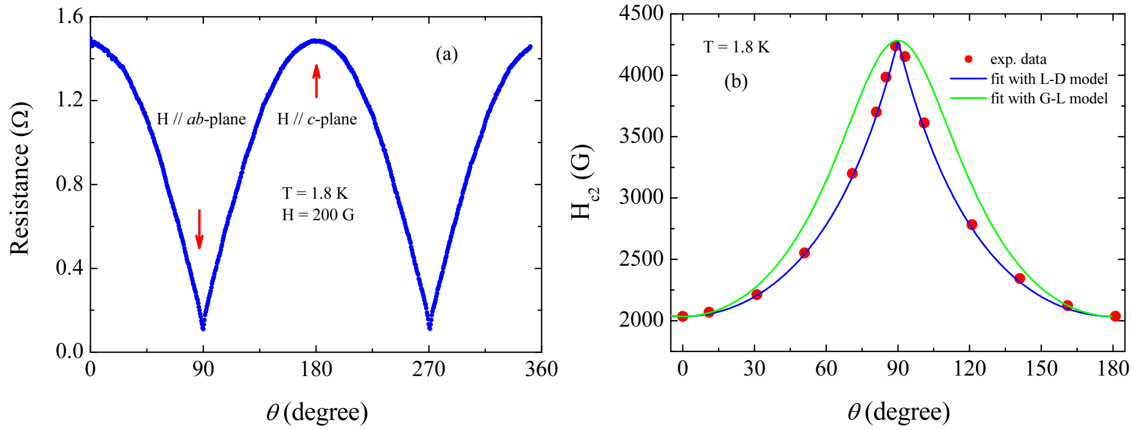

Fig. 3 (a) Angular dependence of resistance in a field of 200 G measured at 1.8 K. (b) Angular dependence of the upper critical field H_{c2} at 1.8 K. The solid points are experimental data, whereas the blue and green curves are fitting to L-D and G-L model, respectively.

Figure 3(a) shows angular dependence of resistance in a field of 200 G measured at 1.8 K, where 0° and 90° corresponds to field parallel and perpendicular to the *c*-axis, respectively. A cusp-like feature at 90° with a smaller resistance and a rounded shape at 0° with a larger resistance indicate a prominent anisotropy in $H_{c2}^{ab}(T)$ and $H_{c2}^{c}(T)$ which is in good agreement with the magnetic phase diagram $H_{c2}(T)$ illustrated in Fig. 2(a). Furthermore, angular dependence of the upper critical field at 1.8 K extracted from $R(H)$ measurements at various angles is revealed in Fig. 3(b). An attempt is made to compare the behavior with the two following models. The first model is anisotropic Ginzburg-Landau (G-L) theory [12], which is valid when the interlayer spacing is much smaller than *c*-direction coherence length. In this case, the upper critical field depends on the angle between the superconducting layers and the applied field through

$$(H_{c2}(\theta)\cos\theta / H_{c2}^{c})^2 + (H_{c2}(\theta)\sin\theta / H_{c2}^{ab})^2 = 1. \tag{1}$$

The second model is based on Lawrence-Doniach (L-D) theory, which assumes that there is a weak coupling between the superconducting layers in the 2D limit [13]. In this case, the angular dependence of the upper critical field is found to be

$$\left| H_{c2}(\theta)\cos\theta / H_{c2}^{c} \right| + (H_{c2}(\theta)\sin\theta / H_{c2}^{ab})^2 = 1. \tag{2}$$

It should be mentioned that a rounded shape at 90° in $H_{c2}(\theta)$ is a signature of the G-L model, whereas the L-D model produces a sharp cusp at 90°. As shown in Fig. 3(b), a cusp-like feature at 90° is observed and the L-D model gives a better fit to the data than the G-L model does, strongly suggesting that the InN film is a quasi-2D superconductor. It is likely that a disorder-induced indium layer along the *ab*-plane is responsible for the quasi-two-dimensional superconductivity.

4 Conclusion

In summary, extensive magnetotransport measurements on InN films have revealed several key features of this novel superconductor. (1) There is a single species of charge carrier with single scattering time at all points on the Fermi surface. (2) The anisotropy parameter γ deduced from $H_{c2}^{ab}(0)/H_{c2}^{c}(0)$ is 2.1. (3) The angular dependence of the upper critical field suggests that the InN film is a quasi-2D superconductor.

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