Superconductivity of InN observed in the magnetoresistance at low temperature

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Abstract. We report on the superconductivity of n-type InN. There is an optimum carrier density for the occurrence of the superconductivity. The lowest carrier density is limited by the Mott transition of \(n_c=2 \times 10^{17}\) cm\(^{-3}\) and the highest density is limited by the superconductivity to metal transition of \(n_i \sim 7 \times 10^{20}\) cm\(^{-3}\). We propose a mechanism where the occurrence of the superconductivity is related to the presence of In-In chains of finite lengths in the \(ab\) plane. The In-In chains, which originate from the inversion domains of InN grown on sapphire (0001) and elongate along [11\(\overline{2}0\)], are coupled to form micro Josephson-junctions.

1. Introduction

Among the group III-nitride semiconductors, InN is a key material for optical and high temperature device applications\cite{1}. Since the first observation of superconductivity around 3 K in InN with a narrow band gap energy of \(\sim 1\) eV\cite{2}, there has been much controversy over the electronic properties of InN, including the band gap energy\cite{3}. From the investigation of the magnetoresistance at low temperature, we have reported there is a resistivity anomaly originating in the carrier localization along [10\(\overline{1}0\)] in the \(ab\) plane, but that it is not observed along [11\(\overline{2}0\)]\cite{4}. The Shubnikov-de Haas oscillation shows that InN has a spherical Fermi surface and its radius increases according to the increase of the carrier density, whereas there is an additional structure observed when the field is perpendicular to the \(ab\) plane.

In this report we will present the carrier density \((n_c)\) dependence of the superconducting transition temperature based on the previous reports. To make clear the superconducting properties of InN, we will compare the magnetoresistance of InN which shows superconductivity with that which does not. We will discuss the possibility of a structure-sensitive low dimensional metallic band in InN based on the results of Shubnikov-de Haas oscillation, and propose a mechanism of the anisotropic superconductivity in terms of the metallic band which, originating from the inversion domain of InN, forms in the \(ab\) plane of In atoms.

2. Experimental procedure

The InN investigated was grown on sapphire (0001) substrates by MBE and MOCVD methods \cite{5, 6, 7, 8, 9, 10, 11}. The film resistance was measured by a standard four-terminal technique using a dc and lock-in amplifier at low frequency. The temperature dependence of the resistance
was measured at the Grenoble High Magnetic Field Laboratory using a dilution refrigerator with in-situ rotation in a 23 T resistive magnet, and at the High Field Laboratory for Superconducting Materials of Tohoku University using a He\textsuperscript{3} cryostat equipped with a 15 T superconducting magnet. All of the InN films investigated had a hexagonal structure and their c axis was perpendicular to the sapphire (0001) plane. The orientation of InN [1\bar{2}10] was parallel to that of Al\textsubscript{2}O\textsubscript{3}[10\bar{1}0]. We determined the lattice constants of InN to be 3.53(6) Å for a-axis and 5.70(9) Å for c-axis as average of the investigated samples. These values are much smaller than those reported by Tansley et al. (a=3.548Å, c=5.760Å\textsuperscript{12}).

3. Results

We measured $n_e$ dependence of the superconducting transition temperature of InN using more than 100 samples\textsuperscript{6}. Typical temperature dependence of the resistivity is shown in Fig. 1.

![Temperature dependence of the resistance of InN grown by MOCVD at different growth temperatures.](image1)

Figure 1. Temperature dependence of the resistance of InN grown by MOCVD at different growth temperatures. The carrier densities of the samples are 4.5 (no.753), 6.5 (no.754), 5.8 (no.756) and 6.8 (no.757) in $10^{20}\text{cm}^{-3}$ unit, respectively.

![Resistance of an InN sample as a function of magnetic field at 0.5, 1.7, 3.0 and 4.2 K.](image2)

Figure 2. Resistance of an InN sample as a function of magnetic field at 0.5, 1.7, 3.0 and 4.2 K. The field is applied perpendicular to $ab$ plane and to $c$ axis, and the measurement current is along [10\bar{1}0].

The samples shown here were grown by MOCVD under almost the same growth conditions except the growth temperature\textsuperscript{6}. The optimum growth temperature for the occurrence of the superconductivity is within 615±5°. When $n_c>5\sim9\times10^{20}\text{cm}^{-3}$, InN does not show superconducting transition and remains in a metallic condition, and so we can say that there is a superconductor to metal transition when $n_c\sim7\times10^{20}\text{cm}^{-3}$. Samples containing polycrystalline phases (e.g. no.757) show a very steep and clear resistivity change at 3.4 K. On the other hand, samples like no.753, which have a less polycrystalline phase, show a gradual decrease of resistivity around 3 K and reach zero resistivity at 1.8 K.

Figure 2 shows the the magnetic field (B) dependence of the resistance at 4.2, 3.0, 1.7 and 0.5 K. The sample was grown by MBE and does not show superconductivity\textsuperscript{4}. When B $\perp ab$ plane, there is a drastic change of magnetoresistance between 4.2 K and 3.0 K, which is due to the carrier localization in the $ab$ plane\textsuperscript{4}. This localization is not observed when B $\perp c$ axis. The frequency and the amplitude of SdH are not dependent on temperature. The Hall carrier density $n_H$ shows a strong temperature dependence between 4.2 K and 3K, and the $n_H$ at 3 K becomes almost one tenth of that obtained at 4.2 K. Hence there is a big and drastic change in the electron distribution between 4.2 K and 3 K in the InN which does not show superconducting transition.
4. Discussion
When InN shows a superconducting transition, the resistivity is not strongly dependent on
temperature, so we must determine the superconducting transition temperature ($T_c$) where the
resistivity becomes half of that of normal state. When the resistivity does not reach 50% at
the lowest temperature of measurements, we estimate $T_c$ from the extrapolation. When the
resistivity change is less than 10% at 0.5 K, we set $T_c=0$ K. In Fig. 3 we plot thus defined $T_c$
as a function of $n_e$ using the reported data. All of the samples show a transition temperature
below 3.4 K, $T_c$ of bulk In.

There is an optimum carrier density for the occurrence of superconductivity. At present there
is no report of InN with a carrier density lower than $n_e=4\times10^{17}\text{cm}^{-3}$, and the sample with this
$n_e$ becomes superconductor at $T_c=0.5$ K. Hence the lowest limit of the transition should be $n_c$, the Mott transition.

As for the highest limit of $n_e$, we have reported on the existence of a superconductor to
insulator transition around $5\times10^{20}\text{cm}^{-3}$[13], where the Cooper pairs are localized due to the
increase of disorder. When $n_e$ is larger than $n_i$, superconductivity to metal transition, the
carriers are scattered by strong disorder, and InN remains in a metallic condition.

![Figure 3](image-url)

**Figure 3.** Summary of the reported carrier density dependence of the superconducting
transition temperature of InN; ■ Ref.[6], ▽ Ref.[14], △ Ref.[4], ● Ref.[15], □ Ref.[16].
The indications of $n_c$ and $n_i$ are the lower and the upper limits of $n_e$ for the occurrence of the superconductivity.

![Figure 4](image-url)

**Figure 4.** Electronic structure of InN illustrated assuming the band gap energy of 0.64
eV and $n_e\sim2.2\times10^{18}\text{cm}^{-3}$. The free electron effective mass was calculated assuming a non-
parabolic ($E_p=10$ eV) dispersion. There is a spherical Fermi surface denoted by A. There
is an additional structure of a flat ellipsoid denoted by B, which has the largest diameter in the
a-b plane.

From the angle dependence of the SdH signals, we proposed a band structure at the
fundamental gap[4], which is shown in Fig. 4. For the drawing, we use the band gap energy
of 0.64 eV assuming a non-parabolic dispersion for the conduction band so as to meet the $n_e$
dependence of the photoluminescence spectra[17]. The SdH oscillation shows that InN has a
spherical Fermi surface denoted by A with a radius $k_A$ that increases according to the increase
of $n_e$. The structure observed when the field is perpendicular to the a-b plane is drawn as a flat
ellipsoid with the largest radius $k_B$, which is denoted by B. The energy position of the latter
should be lower than that of the former because $k_A$ increases according to the increase of $n_e$. 
while \( k_B \) does not. This suggests B has a limited volume and is fully occupied, and that the carriers introduced into the sample lift the Fermi level of A.

The superconductivity of BCS theory is based on the Thomas-Fermi screening of electrons, where the screening length is given by \( 1/k_F \). As was reported before[4], \( 1/k_F \) of InN is \( \sim 100 \) \( \text{A} \), which is much larger than the value of conventional (\( \sim 1 \) \( \text{A} \)) BCS superconductors. In this case, the strong correlation between the electrons must play a significant role for the occurrence of the superconductivity of InN. When InN does not show superconductivity, it has a special electronic band spread in the \( ab \) plane, and below 3K, the electrons travelling along [10\( T \)0] localize strongly[4]. When InN shows superconductivity, it has glassy-vortex solid and its superconducting current is tunneling through micro Josephson-junctions mainly in the \( ab \) plane[16]. In either case, most of the InN remains in a normal, or semiconductor condition, indicating that the superconductivity of InN should be considered as a “superconductivity of a disorder-induced indium thin-film”.

At present we consider that the band B is caused by In-In chains spread in the a-b plane with finite lengths[18]. The In-In chains, which originate from the inversion domains of InN grown on sapphire (0001) substrate and elongate along [1\( 1 \)2\( 0 \)], are coupled to form micro Josephson-junctions[16]. At high temperatures, bands A and B are connected electrically, because In-In chains are embedded in InN. When the temperature decreases, the difference between these two bands becomes obvious and the electrons belonging to B localize. Below 3.4 K band B contributes to the negative magnetoresistance shown in Fig. 2, Cooper pair generation and to the occurrence of superconductivity.

5. Conclusion
We have presented superconductivity data from a number of InN samples with different carrier densities. There is an optimum carrier density for the occurrence of superconductivity and the lower limit is determined by the Mott transition and the upper limit by the superconductor to insulator transition.

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