Single－crystal growth of Nb films onto molecular beam epitaxy grown (001)InAs

著者	Akazaki Tatsushi, Nitta Junsaku, Takayanagi Hideaki
journal or publication title	Applied Physics Letters
volume	59
number	16
page range	2037-2039
year	1991
URL	http://hdl.handle.net/10097/51581

doi: 10.1063/1.106124

Single-crystal growth of Nb films onto molecular beam epitaxy grown (001)InAs

Tatsushi Akazaki, Junsaku Nitta, and Hideaki Takayanagi
NTT Basic Research Laboratories, 3-9-11 Musashino-shi, Tokyo, 180 Japan

(Received 15 April 1991; accepted for publication 29 July 1991)

Thin Nb films are grown by electron beam evaporation in an ultrahigh vacuum system on molecular beam epitaxy grown (001)InAs epitaxial layers. The Nb on InAs grows as a single-crystalline deposit at a substrate temperature of 200 °C. The orientation relation is (001)Nb//(001)InAs with [110]Nb//[110]InAs, which is different from Nb growth on GaAs. The interface between Nb and InAs features a crystal-disordered layer with a thickness of 1–2 nm, which provides relaxation from lattice mismatch. Critical current measurement of Nb/InAs/Nb junctions shows that the crystal-disordered layer does not affect the superconducting characteristics of the junctions.

Metal-semiconductor junctions have been intensively studied due to both technological and scientific interest. Epitaxial metal growth on single-crystal semiconductor is very attractive for device applications, such as the metal-base transistor,[1] as well as for scientific research, such as a metal-semiconductor superlattice study. A metal-semiconductor superlattice is expected to realize exciton mechanism of superconductivity at the metal-semiconductor interface, in which the attractive interaction between electrons comes from excitation of excitons.[2,3] In addition, the superconductor–semiconductor superlattice using the superconducting proximity effect shows the dimensional crossover of the critical magnetic field.[4,5] A single-crystal metal layer on a semiconductor substrate is necessary for these studies because the epitaxial semiconductor layer must be subsequently grown on this metal layer. The growth mechanism on GaAs has been investigated for many metals, such as Al, Au, Mo, W, and Nb.[3,6–9] These results have indicated the optimum growth condition for the epitaxial metal growth on GaAs. However, the study of metal growth on III–V compound semiconductor is almost restricted to the cases on the GaAs substrate. Note that we have studied semiconductor-coupled superconducting junctions using the superconducting proximity effect.[10–13] The ideal superconductor–semiconductor interface is necessary to clarify the boundary conditions of the semiconductor-coupled superconducting proximity effect.[14] The epitaxial metal growth on single-crystal semiconductor is considered as one of the methods that can realize the ideal superconductor–semiconductor interface. This method helps to advance these studies on the metal-semiconductor superlattice and the semiconductor-coupled superconducting proximity effect.

In this letter we report the growth of Nb by electron beam evaporation (EB) on molecular beam epitaxy (MBE) grown InAs epitaxial layers. Nb films were made under two different conditions. These films are compared from the viewpoints of crystallinity, interface morphology, and superconducting properties.

The MBE/EB system consists of a preparation chamber, a metal-evaporation chamber, and an MBE chamber. The metal-evaporation chamber is separated from the MBE one so that As is not incorporated as the impurity into Nb films. Thus Nb is immediately deposited after the growth of InAs under a residual gas pressure of $\sim 1\times 10^{-10}$ Torr and there is no wait for the As background pressure to minimize. Since the InAs surface is exposed only to 0.1 L ($=$Torr×s), it does not adsorb oxygen atoms before the Nb deposition. First, a *p*-type InAs buffer layer with a thickness of 1.0 μm was grown on a *p*-type InAs substrate. This was followed by the growth of an *n*-type InAs channel layer with a thickness of 0.4 μm. Si and Be were used as the *n* and *p*-type dopants, respectively. The InAs layers were deposited at a growth rate of 0.3 nm/s and at a growth temperature of 480 °C. Next, after transferring the sample into the metal-evaporation chamber, a Nb layer with a thickness of 0.1 μm was deposited by electron beam evaporation at growth rates between 0.6 and 1.0 nm/s and at substrate temperatures T_S of 50 and 200 °C. A growth rate faster than that previously reported[9] was adopted to reduce impurity incorporation into Nb.

The crystallography of the sample was analyzed by transmission electron microscopy (TEM). Since Nb is a much harder material than InAs, cross-sectional samples for TEM were prepared by using the Ar ion milling technique with a low angle to improve the thickness uniformity at the interface region. Figures 1(a) and 1(b) are electron diffraction pattern and cross-sectional TEM image of the sample deposited at $T_S = 200$ °C, respectively. In Fig. 1(a), the diffraction pattern for Nb shows clear spots. This result shows that the Nb film grows as a single-crystalline deposit at least in the observation area (0.4 μm square). The grain boundary cannot be observed in the Nb surface by the scanning electron microscopy. These results suggest that the Nb film grows as a single crystal in the wide area. It also indicates that the epitaxial arrangement is (001)Nb//(001)InAs with [110]Nb//[110]InAs, which is well known as Baker–Nutting 45 (BN45) epitaxy.[15] In addition, it was experimentally confirmed that this Nb had epitaxial (001) orientation from the x-ray diffraction pattern. As shown in the TEM image, the Nb/InAs interface has a crystal-disordered layer with a thickness of 1–2 nm and a Nb crystal is inclined at less than 10°. This crystal-disordered layer seems to consist of Nb atoms and to provide relaxation of misfit which is caused by lattice mis-

0003-6951/91/412037-03$02.00

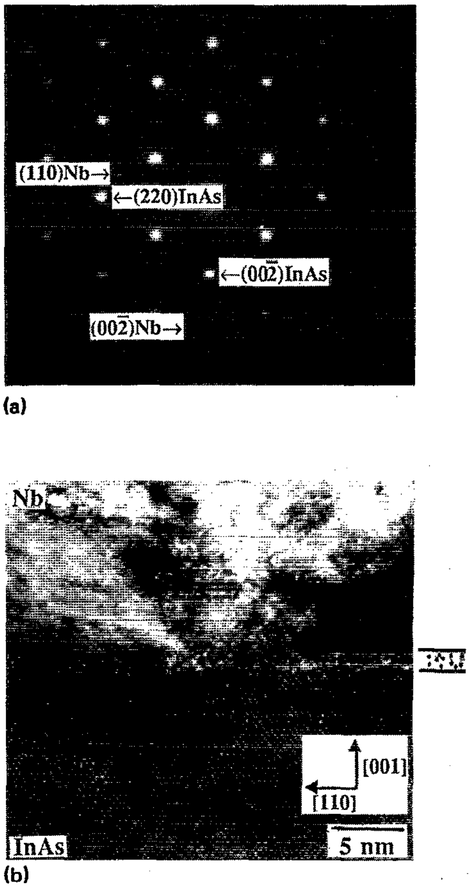

FIG. 1. (a) Electron diffraction pattern and (b) cross-sectional TEM image of the sample deposited at $T_S = 200\,^\circ\mathrm{C}$. Inset: a crystal-disordered layer.

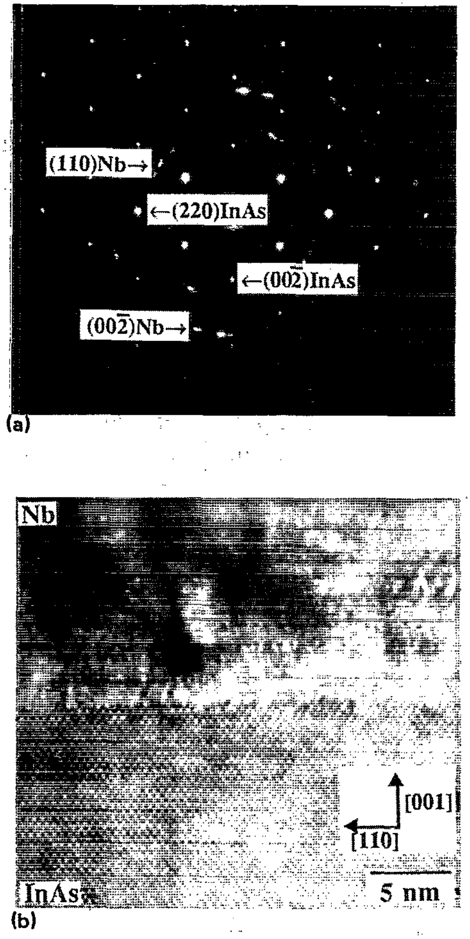

FIG. 2. (a) Electron diffraction pattern and (b) cross-sectional TEM image of the sample deposited at $T_S = 50\,^\circ\mathrm{C}$.

match between Nb and InAs. Figures 2(a) and 2(b) are electron diffraction pattern and cross-sectional TEM image of the sample deposited at $T_S = 50\,^\circ\mathrm{C}$, respectively. We cannot observe the ring pattern but a few broad spots in the diffraction pattern from Nb. This result shows that the Nb film grows as a polycrystalline deposit and few large Nb crystals are included in the observation area. The polycrystalline growth of Nb is caused by the decrease in diffusivity with decreasing substrate temperature. The TEM image of Nb shows that the interface is sharp in the atomic-scale range and does not have a crystal-disordered layer as seen at $T_S = 200\,^\circ\mathrm{C}$. Thus, we consider obtaining the suitable Nb/InAs interface in the case of $T_S = 50\,^\circ\mathrm{C}$ to clarify the boundary conditions of the semiconductor-coupled superconducting proximity effect.

Grovenor *et al.* studied the epitaxial relationship between fcc metal substrates and various bcc metal deposits.[15] They theoretically showed that for a deposit/substrate lattice parameter ratio of $r < 0.767$ BN epitaxy {(100)bcc//(100)fcc, [001]bcc//[011]fcc} was prevalent, and that BN45 epitaxy could be obtained only for $r > 0.915$ [in the intermediate range another epitaxy, called A, with (110)bcc‖(100)fcc was obtained]. The lattice parameter of Nb and InAs is 3.3067 and 6.0584 Å, respectively. The experimental result for Nb/(001)InAs with a lattice parameter ratio of $r = 0.546$ cannot simply be explained in terms of the Grovenor theory. It should be noted that the Nb/InAs system epitaxy [BN45 epitaxy, $r = 0.546$] differs from that of Nb/GaAs [BN epitaxy, $r = 0.585$].[9] This result reveals that BN45 epitaxy is more stable than BN epitaxy, when r is 0.546. For this reason, we maintain that $r = 0.916$ assuming that a Nb atom is placed on every other Nb atom for the [100] and [010] direction. The experimental result for Nb/(001)InAs can be explained in terms of the Grovenor theory with this assumption. The crystal-disordered layer is thought to consist of this Nb layer, which has many defects due to the shift of a normal atom position. These defects disappear during growing a few monolayers of Nb, because Nb gets to be stable in a normal atomic position.

Nb/InAs/Nb superconducting junctions were made using these Nb/InAs systems in order to investigate the superconducting properties. The structure of a Nb/InAs/Nb superconducting junction is schematically illustrated in Fig. 3. Nb electrodes were patterned by a reactive ion etching (RIE) technique.[16] The superconducting critical current I_C of the junction was measured. The critical-current normal resistance product is described as

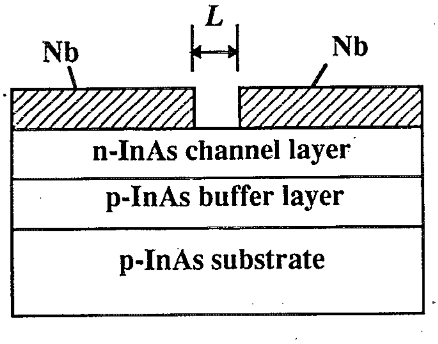

FIG. 3. Schematic diagram of the fabricated junction structure.

$$I_C R_N = \frac{\pi}{8ek_BT}\left[\frac{\Delta_N(T)}{\cosh(L/2\xi_N)}\right]^2 \frac{L}{\xi_N}, \qquad (1)$$

where L is the length between two Nb electrodes, ξ_N is the coherence length in the normal metal, R_N is the normal resistance and $\Delta_N(T)$ is the induced pair potential at the superconductor normal interface.[17–19] The superconducting characteristics of the junction using Nb at $T_S = 200$ and 50 °C are shown in Table I. Nb electrodes of both samples have the same superconducting critical temperature T_C of 8.6 K. The difference of crystallinity does not affect the superconducting critical temperature. Therefore, the Δ_N of both junctions can be compared from the viewpoint of the interface morphology. The results show that L, ξ_N, I_C, and R_N of the junction using Nb at $T_S = 200$ °C are almost the same as those at $T_S = 50$ °C. From Eq. (1), the obtained ratio of Δ_N between the junction using Nb at $T_S = 200$ °C and $T_S = 50$ °C is 0.9. This result shows that the crystal-disordered layer does not affect the superconducting characteristics of the junctions.

TABLE I. Superconducting characteristics of the junction using Nb, where T_S is the substrate temperature deposited a Nb film, L is the length between two Nb electrodes, n is the carrier concentration of InAs, μ is the mobility of the InAs, ξ_N is the coherence length in InAs, I_C is the superconducting critical current and T_C is the superconducting critical temperature of Nb.

	$T_S = 200$ °C	$T_S = 50$ °C
L (μm)	0.38	0.38
n (cm^{-3})	2.5×10^{19}	9.7×10^{18}
μ (cm^2/V s)	2100	4300
ξ_N (μm) at 2.2 K	0.18	0.21
I_C (μA) at 2.2 K	70	67
R_N (Ω)	0.051	0.073
T_C (K)	8.6	8.6

In summary, Nb films were grown as a single-crystalline deposit on (001)InAs planes at $T_S = 200$ °C in an ultrahigh vacuum system. The orientation relation is (001)Nb//(001)InAs with [110]Nb//[110]InAs, called BN45 epitaxy. The interface between Nb and InAs features a crystal-disordered layer with a thickness of 1–2 nm, which provides relaxation from lattice mismatch. It was found that this crystal-disorder layer does not affect the superconducting characteristics strongly. We can consider that this Nb/InAs interface is sufficient to clarify the boundary conditions of the semiconductor-coupled superconducting proximity effect. These results should also help to advance the metal-semiconductor superlattice study.

The authors would like to thank to Dr. Hidetoshi Takaoka for the transmission electron microscopy observation. They also express their thanks to Azusa Matsuda and Koh Inoue for their valuable discussions and to Takehisa Kawashima for the sample preparation.

[1] D. V. Geppert, Proc. IRE **50**, 1527 (1962); D. Khang, *ibid.* **50**, 1534 (1962).
[2] D. Allender, J. Bray, and J. Bardeen, Phys. Rev. B 7, 1020 (1973).
[3] M. Tonouchi, K. Hashimoto, Y. Sakaguchi, S. Kita, and T. Kobayashi, *Extended Abstracts of the 1987 International Superconductivity Electronics Conference* (The Japan Society of Applied Physics, Tokyo, 1987), p. 170.
[4] S. T. Ruggiero, T. W. Barbee, Jr., and M. R. Beasley, Phys. Rev. Lett. **45**, 1299 (1980).
[5] S. Takahashi and M. Tachiki, Phys. Rev. B **33**, 4620 (1986).
[6] M. Missous, E. H. Rhoderick, and K. E. Singer, J. Appl. Phys. **59**, 3189 (1986).
[7] T. Yoshiie, C. L. Bauer, and A. G. Milnes, Thin Solid Films **111**, 149 (1984).
[8] J. Bloch, M. Heiblum, and Y. Komem, Appl. Phys. Lett. **46**, 1092 (1985).
[9] M. Eizenberg, D. A. Smith, M. Heiblum, and A. Segmüller, Appl. Phys. Lett. **49**, 422 (1986).
[10] T. Kawakami and H. Takayanagi, Appl. Phys. Lett. **46**, 2449 (1985).
[11] H. Takayanagi and T. Kawakami, Phys. Rev. Lett. **54**, 92 (1985).
[12] T. Akazaki, T. Kawakami, and J. Nitta, J. Appl. Phys. **66**, 6121 (1989).
[13] K. Inoue and H. Takayanagi, Phys. Rev. B **43**, 6214 (1991).
[14] P. G. de Gennes, Rev. Mod. Phys. **36**, 225 (1964); *Superconductivity of Metals and Alloys* (Benjamin, New York, 1969).
[15] C. R. M. Grovenor, A. P. Sutton, and D. A. Smith, Scripta Metall. **18**, 939 (1984).
[16] The structure and the fabrication process of the Nb/InAs/Nb junction (unpublished).
[17] J. Seto and T. Van Duzer, in *Low Temperature Physics LT-13*, edited by K. D. Timmerhous, W. J. O'Sullivan, and E. F. Hammel (Plenum, New York, 1974), Vol. 3, p. 328.
[18] K. K. Likharev, Rev. Mod. Phys. **51**, 101 (1973).
[19] H. Takayanagi and T. Kawakami, *Technical Digest International Electron Devices Meeting* (The Institute of Electrical and Electronics Engineers, Washington, DC, 1985), p. 98.