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Low-dimensional electron transport properties in InAs/AlGaSb mesoscopic structures

M. Inoue, T. Sugihara, T. Maemoto, S. Sasa, H. Dobashi, S. Izumiya
Department of Electrical Engineering, Osaka Institute of Technology,
Asahi-ku-, Ohmiya, Osaka 535, Japan

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We report on the successful fabrication and electrical transport properties of single quantum wires fabricated by using InAs/AlGaSb heterostructures. Magnetotransport and high electric field characteristics have been measured on the various size of quantum wires. From comparison with the channel length-dependence of I–V characteristics of the different size quantum wires, we try to develop a comprehensive understanding on the quasi-one dimensional electron transport in InAs from the nearly ballistic regime to the hot electron condition.

The fabrication and characteristics of superconducting weak link InAs/Pb:In devices are also reported. The modulation of differential conductivity has been observed by the gate bias voltage between the superconducting Pb–In contacts.

Key words: InAs, 1D transport, weak links.

1. Introduction

The study of ballistic and quasi-one-dimensional (1D) electron transport in mesoscopic structures has become a very attractive research field from the viewpoint of new types of quantum effect devices. A significant enhancement of 1D electron mobility due to the suppression of ionized impurity scattering has been predicted by Sakaki [1]. Electron–phonon and electron–electron scatterings in quantum wires were also theoretically studied predicting a significant difference from that in the two-dimensional electron gas [2, 3]. A decrease of the electron mobility, however, was measured in GaAs/AlGaAs with decreasing wire width and increasing wire length, which was attributed to roughness scattering [4]. Meanwhile, clear evidence of 1D density of states and mobility modulation of 1D electrons was demonstrated in GaAs/AlGaAs quantum wires (QWs) by Ismail *et al.* [5].

Due to the rapid progress of nanostructure fabrication by using a variety of semiconductor heterostructures, mesoscopic quantum effects can be manifest at higher temperatures above the liquid helium temperature. For further development of these devices, the operating temperature is the center of interest. InAs-based heterostructures have potential for observation of quantum effects at higher temperatures, due to the small effective mass of electrons and the strong electron confinement in InAs/Al(Ga)Sb [6]. Quantized conductance of ballistic constrictions have been observed at relatively higher temperatures around 30 K [7] and 77 K [8] in InAs heterostructures.

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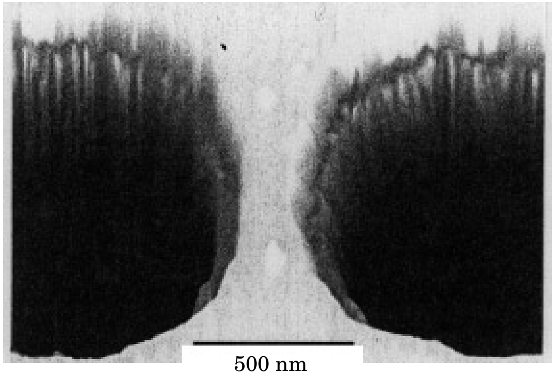

Fig. 1. Atomic force micrograph (AFM) of a single QW.

In this paper, we report on the investigation of 1D electron transport in single quantum wires fabricated on InAs/AlGaSb heterostructures. Magnetoresistance measurements of the 1D wires with different width have been performed at 4.2 K. The high-field transport properties have been also measured on various mesoscopic structures at 4.2 K and 77 K. The size-dependent transport properties measured on the different channel length and width are compared, and we try to develop a comprehensive understanding on the 1D electron transport from the nearly ballistic regime to the hot electron condition.

Since InAs is also a suitable semiconductor as a superconducting weak link material, InAs heterostructures have been used for weak link devices [9, 10]. The fabrication and device characteristics of InAs/Pb:In superconducting weak link devices with a gate electrode are also presented [10].

2. Fabrication of mesoscopic structures

InAs/AlGaSb heterostructures grown by molecular beam epitaxy (MBE) have been fabricated by conventional photolithography and wet chemical etching. The structure consists of a GaAs buffer layer (250 nm), an AlSb buffer layer (1.5 μm), an AlGaSb barrier layer (200 nm), an InAs channel layer (15 nm), an AlGaSb upper layer (15 nm), and a GaSb cap layer (10 nm). The structure was grown on a semi-insulating GaAs substrate and was nominally undoped. The substrate temperature was set to 600 $^\circ$C during the growth of the GaAs buffer, 640 $^\circ$C and 450 $^\circ$C for the AlSb buffer layer and the InAs layer or above, respectively. The measured mobility and density of the two-dimensional (2D) electrons spanned the ranges 0.7–2.8 $\times\ 10^5$ cm^2(Vs)$^{-1}$ and 0.8–1.1 $\times\ 10^{12}$ cm^{-2} at 77 K, respectively.

In order to study the one-dimensional transport properties, we have fabricated QWs by using conventional photolithography and wet chemical etching. Many kinds of samples with different wire width (0.1 to 0.7 μm) and wire length (1 to 10 μm) were fabricated to study systematically the transport properties. The fabrication process began with the definition of the wires by conventional photolithography. The widths of the wires were varied by stepwise etching using a phosphoric acid based etchant. Figure 1 shows a typical atomic force microscope (AFM) image of the QW. The width of top barrier, GaSb and AlGaSb, is a little narrower than that of the InAs and lower layers, which is due to the effect of selective etching of the antimonide layer during the process of developing the photoresist using Microposit MF319. The effective channel width, which is responsible for current flow, has been estimated by the magnetotransport measurements and the plots of conductance as a function of nominal width of various QWs.

The superconducting weak link device was also fabricated by a similar process using conventional photolithography, lift-off, and chemical etching [10]. Since the minimum design length of the used photomask

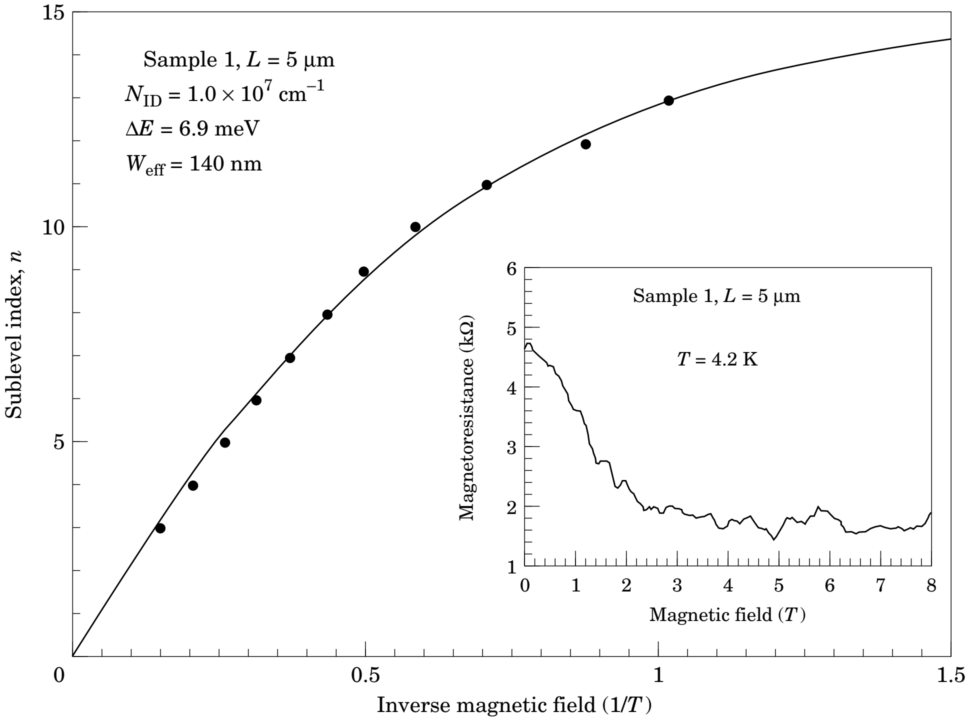

Fig. 2. Sublevel index n versus inverse magnetic field B^{-1}. The inset shows the magnetoresistance of a single QW at 4.2 K.

was 0.38 mm, the gate electrode ranging from 0.4 to 0.6 μm wide has been successfully fabricated between the Pb:In alloyed superconducting electrodes.

3. Electron transport in quantum wires

The one-dimensional nature of InAs single quantum wires has been investigated by magnetotransport measurements at 4.2 K. Contrary to previous results measured on multiple QWs [11], a large negative magnetoresistance has been observed, as shown in the inset of Fig. 2. The sublevel index, n, is plotted as a function of inverse magnetic field in Fig. 2. By using the relation [12] between sublevel index and inverse magnetic field fitted to the experimental results, we extracted the 1D electron concentration, N_{1D}, and the characteristic frequency, ω_0, defining the strength of the confinement, to be $N_{1D} = 1.0 \times 10^7$ cm^{-1} and $\omega_0 = 1.0 \times 10^{13}$ s^{-1}. The energy separation between 1D subband can be estimated to be 6.9 meV, if a parabolic confined potential is assumed. The effective width W of 1D channel was determined, from N_{1D} and ω_0, to be 140 nm, which is consistent with the effective channel width reduced from the plots of the conductance as a function of the nominal width of various samples.

In order to investigate 1D electron transport from the nearly ballistic regime to the hot electron condition, velocity-field characteristics have been measured at 77 K, and compared with various QWs for different InAs channel width and length. The 1D electron velocity was deduced from the current and the effective channel width obtained from the width-dependent conductance measurements. Two typical InAs heterostructures, Sample 1, $n_s = 1.0 \times 10^{12}$ cm^{-2}, $\mu = 180\,000$ cm^2(Vs)$^{-1}$; Sample 2, $n_s = 0.64 \times 10^{12}$ cm^{-2}, $\mu = 9\,000$ cm^2(Vs)$^{-1}$ at 77 K, were fabricated to many single QWs. The mean free path lengths are estimated to be 3.1 μm (S-1) and 1.2 μm (S-2).

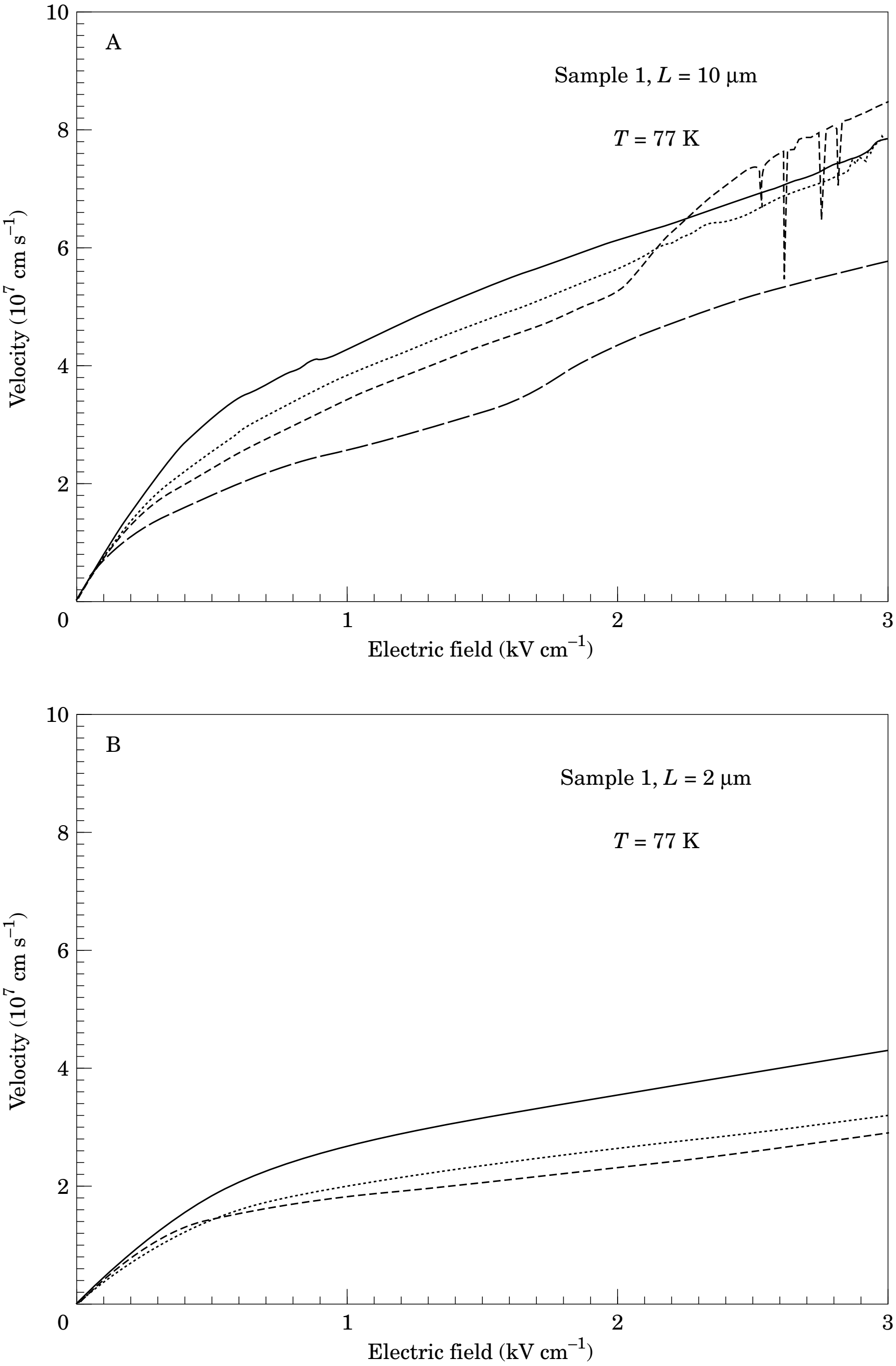

Fig. 3. (A) Velocity-field characteristics of QWs for the channel length $L = 10\ \mu$m. ——: 100 nm; · · · · ·: 130 nm; - - - -: 250 nm; – – –: 730 nm. (B) The characteristics for $L = 2\ \mu$m. ——: 170 nm; - - - -: 280 nm; – – –: 580 nm.

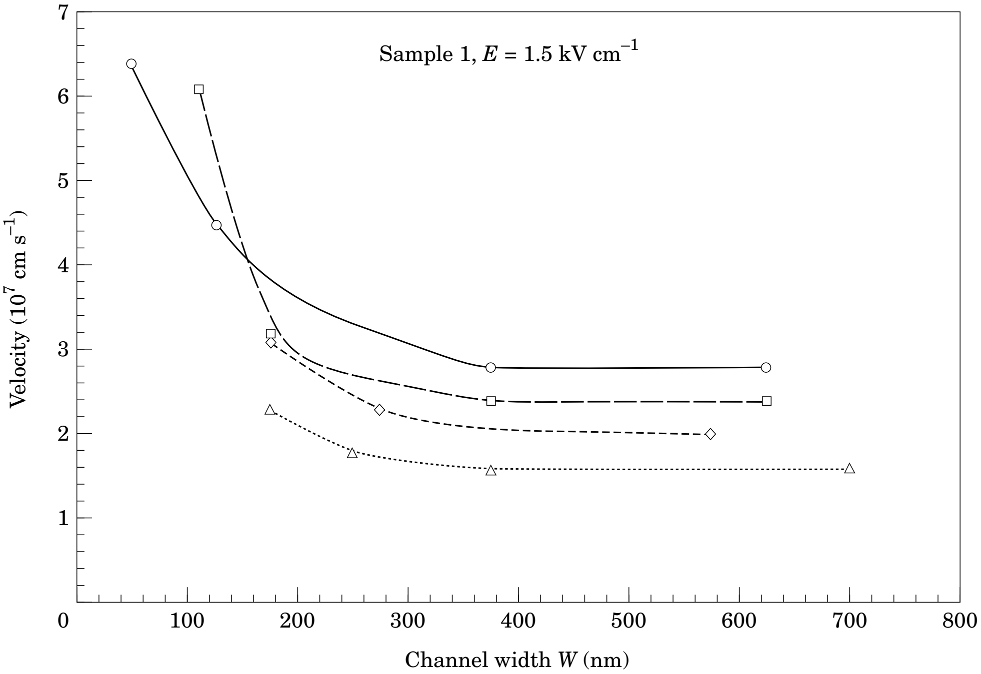

Fig. 4. Velocity at 1.5 kV cm^{-1} versus channel width of QWs for different channel length L. –○–: $L = 10$ μm; –□–: $L = 5$ μm; –◇–: $L = 2$ μm; –△–: $L = 1$ μm.

Figure 3A and B show the velocity-field characteristics for the QWs for the channel length $L = 10$ μm and $L = 2$ μm, respectively. Enhancement of mobility can be observed with decreasing channel width over the whole range of electric field strengths. It should be noted that enhancement of the mobility due to electron confinement into the 1D channel was observed for remarkably long QWs. A similar result has been also obtained for the QWs of Sample 2. The channel width dependencies of the velocity at 1.5 kV cm^{-1} are summarized in Fig.4. A clear increase of velocity with decreasing wire width and increasing wire length was found at electric fields up to 3 kV cm^{-1}. This result is qualitatively consistent with the theoretical predictions of enhanced mobility [1, 2] and completely different from the previous results for GaAs QWs that were dominated by roughness scattering [4]. The marked enhancement of the high field velocity in the narrow QW indicates a reduction of the 1D electron–phonon interaction, and the appearance of singularities in the 1D density of states, which should be more pronounced in the long QWs. In the short QWs, such as $L = 1$ and 2 μm, less than the mean free path l_m, the combined 1D and 2D character and additional effects should complicate the transport as shown in the present results.

4. InAs/Pb:In weak link devices

Superconductive properties induced in a semiconductor can be applicable to high-speed and low-power devices [13]. Because of the suitable transport properties of InAs and InGaAs for weak links, new results have been reported in recent years [14–16]. On the basis of InAs/Pb:In heterojunctions [10], we have made a three-terminal superconducting transistor as shown in Fig. 5. The gate length and channel length are $L_g = 0.7$ and $L_{sd} = 0.9$ μm, respectively. The mean free path and the coherence length are estimated to be $l_m \approx 3.8$ μm and $\xi_c \approx 0.35$ μm for the clean limit at 4.2 K, respectively. L_{sd} is only a little larger than $2\xi_c$, permitting the flow of supercurrent in the InAs channel. Figure 6 shows the characteristics of differential resistance

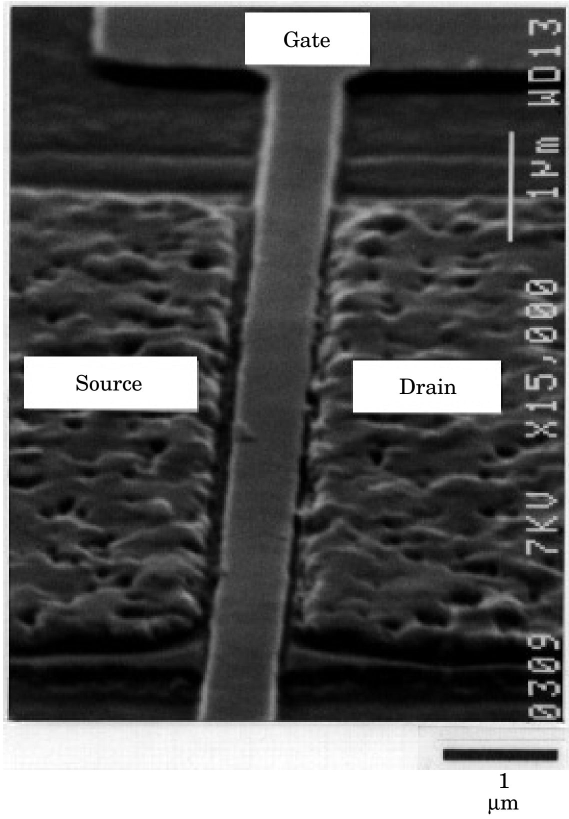

Fig. 5. Scanning electron micrograph (SEM) of the InAs/Pb:In superconducting weak link transistor.

versus drain voltage V_{ds} for the different gate bias conditions. The differential resistance has been changed by the gate bias voltage. Reduction of differential resistance indicates that a superconducting channel can be gradually formed between source and drain contacts. Since the positive gate bias increases the electron density in the channel, the coherence length becomes larger. Therefore, superconducting current can penetrate further from the source and drain contacts. The change of ξ_c was estimated to be about 0.15 μm from the gate bias dependence of the electron density of InAs channel.

5. Conclusion

In conclusion, we have investigated 1D electron transport in InAs QWs fabricated by photolithography and wet chemical etching on a high quality InAs/AlGaSb heterostructures. A large negative magnetoresistance has been observed for the narrow QW at 4.2 K. Although the reason for this negative value cannot be determined from the present data alone, the effect of boundary scattering [17] should be also involved in the present data.

The successfully fabricated smooth InAs QWs have clearly demonstrated the 1D character of the electron transport. The dependence of the electron velocity on channel width and length was systematically measured at 77 K. The enhancement of 1D electron mobility with decreasing the channel width and increasing the channel length was demonstrated, which is qualitatively consistent with the theoretical predictions. Further detailed analyses to develop a QW transistor [11] and superconducting weak link devices should be done in the future.

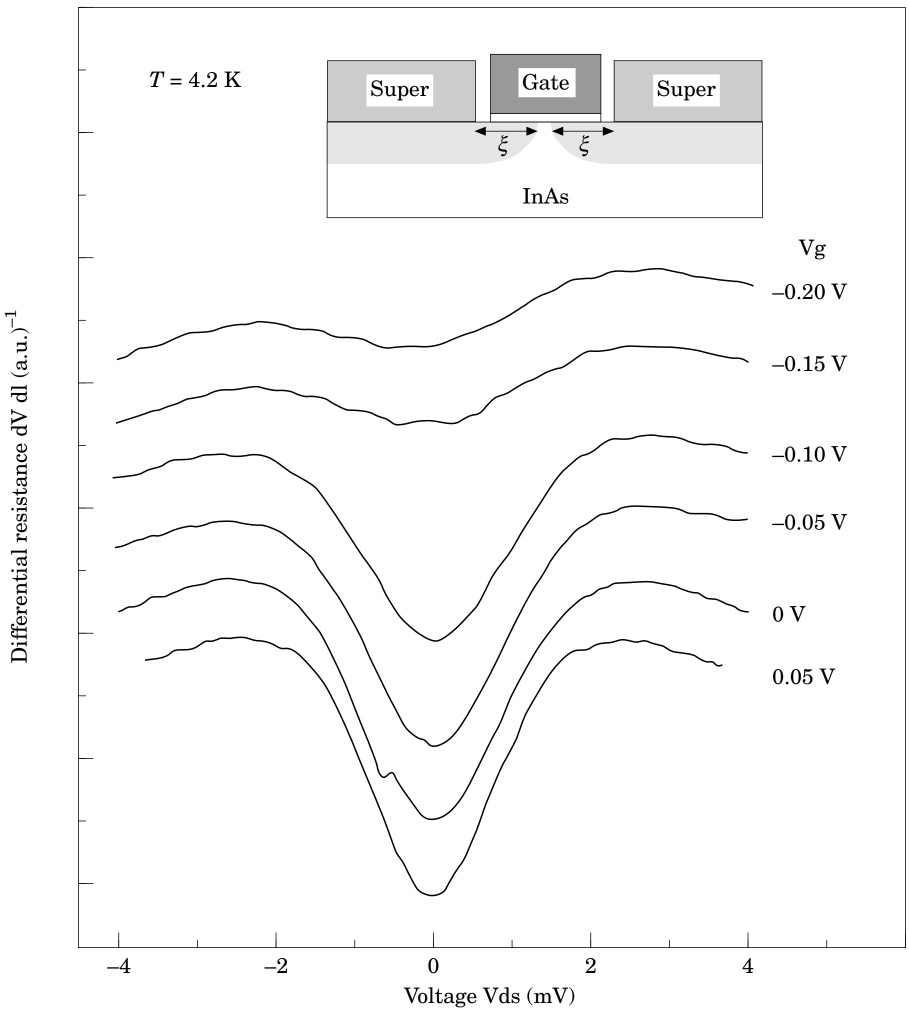

Fig. 6. Conductance modulation of the weak link transistor by a gate bias voltage.

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