Hopping conduction and localized states in p-Si wires formed by focused ion beam implantations

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Localized states in p-Si wires formed in n-Si(100) substrates by selective ion implantation using a focused Ga^+ ion beam have been investigated. The electrical conductance has the temperature dependence of one-dimensional (1D) variable-range-hopping conduction in the temperature range below 50 K, $\sigma=\sigma_0 \exp[-(T_0/T)^{1/2}]$. The magnetoresistance $R(H)$ of p-Si wires at 4.2 K shows the negative and positive magnetoresistances at weak and strong magnetic fields, which have the relation that $R(H)/R_0 \propto \exp(-\beta H)$ and $R(H)/R_0 \propto \exp(\alpha H^2)$, respectively, where R_0 is the resistance without the magnetic field H. These characteristics can be explained by the 1D hopping conduction mechanism under the magnetic field. By expanding a three-dimensional model, we derive an equation of positive magnetoresistance in 1D hopping conduction. From the temperature dependence of conductance and positive magnetoresistance, the localization length, hopping distance, and density of localized states are estimated to be about 2 nm, 8–9 nm and about 10^9 cm^{-1} eV^{-1}, respectively. This result indicates that the carrier transport is confined with the region of a few tens of nanometers. © *1998 American Vacuum Society.* [S0734-211X(98)01304-3]

I. INTRODUCTION

The size of individual devices in ultralarge-scale integrated circuits (ULSIs) is at the submicron scale and, within the next decade, the device dimensions will be reduced to below 100 nm.[1] In such small devices, the device functions will be affected by quantum transport properties. By harnessing the quantum effects such as quantum interference effects, single-electron phenomena and so forth, the development of new devices is also expected.[1–5] Therefore, both the development of semiconductor microfabrication technology and the elucidation of carrier transport phenomena in the low-dimensional system are important.

In our previous work,[6,7] we have developed a successful method to fabricate p-Si wires using the focused ion beam (FIB) doping and investigated the electrical properties of wires. Selective ion implantation by FIB is considered to be one of the simplest methods to realize low-dimensional carrier transport systems. The conducting area of low-doped p-Si wires has been completely controlled by changing the depletion region width in pn junctions with the reverse bias.[6] It has also been found that one-dimensional variable-range-hopping (1D-VRH) conduction is dominant in highly doped wires at low temperatures.[7] However, details of the 1D-VRH systems, such as localization length and so forth, were not clear. In this work, the localization length and hopping distance in the 1D-VRH regime are discussed by measuring magnetoresistance.

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II. EXPERIMENTS

Focused Ga^+ ion beams with a diameter of less than 0.1 μm were used to form p-type conductive wires by scanning the surface of n-type Si(100) substrates with a resistivity of 2–3 Ω cm. The length of p-type wires was 50 μm. The accelerating voltage and beam current of Ga^+ ions was 100 keV and 50–130 pA, respectively. The annealing was performed in order to activate the implanted Ga atoms electrically and to recover implantation-induced damages. The following three samples were prepared: The ion dose and annealing temperature were: (a) 5.6×10^9 cm^{-1} and 600 °C, (b) 3.5×10^9 cm^{-1} and 600 °C, and (c) 5.2×10^9 cm^{-1} and 690 °C, respectively. The annealing was performed in N_2 gas for 30 min. The fabrication conditions are summarized in Table I. Before the FIB implantation, heavily doped p-type regions were formed as electrodes by the conventional ion implantation of BF^+ with a dose of 2×10^{15} cm^{-2} at an accelerating voltage of 30 keV and samples were annealed at 900 °C for 30 min.

The electrical conductance was measured in the temperature range from 4.2 to 300 K by using a liquid He cryostat. In the present experiment, no substrate bias was applied. The magnetoresistance was also measured in the range from 0 to 4 T at 4.2 K by applying magnetic field perpendicular to the direction of current flow.

III. RESULTS AND DISCUSSIONS

A. Temperature dependence

Figure 1(a) shows the temperature dependence of electrical conductivity in a 1D system. The data show the presence of two parallel conduction mechanisms. One is the carrier conduction in the valence band, which has an activation-type temperature dependence due to the carrier activation process

TABLE I. Fabrication condition of p-Si wires.

Sample	A	B	C
Line dose (cm^{-1})	5.6×10^9	3.5×10^9	5.2×10^9
Annealing temp. (°C)	600	600	690

TABLE II. Estimated values of $a\cdot\rho_F$.

Sample	A	B	C
$a\rho_F$(eV^{-1})	487	199	284

to the valence band in the temperature range above 50 K, and the other is 1D-VRH below 50 K, as reported previously,[6,7] in which filamentary quasi-1D paths are considered to be formed.[6,7] For all samples prepared in this experiment, the temperature dependence of electrical conductivity is well fitted by the following relationship below 50 K:[6,7]

$$\sigma=\sigma_0 \exp[-(T_0/T)^{1/2}], \tag{1}$$

where T_0 is a characteristic temperature, and T the absolute temperature. This fact is a characteristic feature of the 1D-VRH conduction and filamentary quasi-1D paths are considered to be formed in the ion-implanted wire region.[7,8] The characteristic temperature T_0 includes information about the localized states in the conductive p-Si region. According to the percolation approach by Butcher and McInnes,[8] the T_0/T of 1D-VRH systems is given by

$$T_0/T=2N_{p1}(T_0'/T), \tag{2}$$

where $k_BT_0'=(a\rho_F)^{-1}$. Here, N_{p1} is the mean number of percolation paths per site in the 1D case, ρ_F the density of localized states at the Fermi level and a the localization length. The value of N_{p_1} is evaluated to be 4.5 by simulation.[8,9] By using these relationships, the values of $a\rho_F$ for each sample can be estimated from the experimental data and are indicated in Table II.

In the VRH system, the electrical conductivity can also be given by the following expression in a percolation approach,[10,11]

$$\sigma\propto\exp(-2r_c/a), \tag{3}$$

where r_c is the critical hopping distance. The temperature dependence of conductivity in VRH systems results from hopping from the fact that the hopping distance has the temperature dependence of $r\propto T^{-p}$, where $p=1/(d+1)$ and d the dimension of the system.[12] Since the whole conductivity is considered to be dominated by the conductivity at a critical hopping distance r_c,[10] the r_c is used to estimate the hopping distance r in the following discussion.

B. Magnetoresistance

Figure 2 shows the magnetoresistance, $R(H)/R_0$, of samples at 4.2 K, where R_0 is the resistance without the magnetic field. The electric field of 200 V/cm was applied for all samples. Negative magnetoresistance (NMR) clearly appears for sample B below 1 T. In the VRH regime, the probability of each hop is affected by the other localized states due to scattering and interference effects in tunneling processes, because the hopping distance exceeds the average interimpurity distance. The magnetic field affects the phase factor of the hopping probability and the negative magnetoresistance is also expected.[13] The magnetic field dependence of NMR in hopping conduction is described by $R(H)/R_0\propto\exp(-\beta H)$ at weak magnetic fields.[13] The experimental results below 1 T in Fig. 2 are explained by this relationship. As discussed later, a hopping distance in sample B is largest in samples, which is considered to correspond to the appearance of NMR in sample B. The $R(H)/R_0$ changes from negative to positive around 2 T for sample B. Above 2 T, the positive magnetoresistance has a relationship of $R(H)/R_0\propto\exp(\alpha H^2)$ for all samples.

The positive magnetoresistance can be explained by the squeeze of the envelope wave function of localized states in magnetic field, which result in the decrease in localization

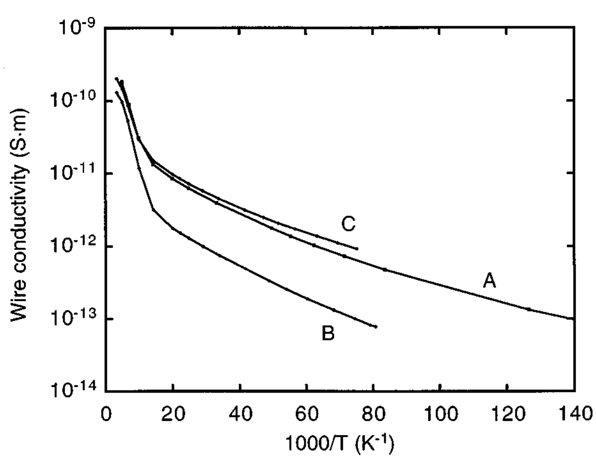

FIG. 1. Temperature dependence of conductivity for samples A, B, and C.

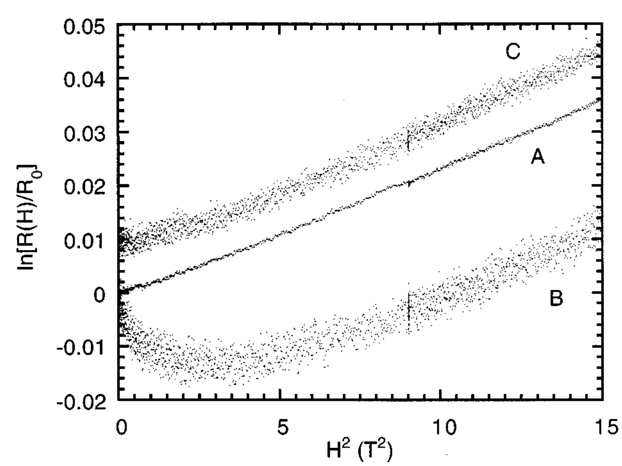

FIG. 2. Normalized magnetoresistance at 4.2 K for samples A, B, and C. The curve of sample C is shifted by +0.01 in order to be distinguished from that of sample A.

length and hopping probability. By a percolation approach in the three-dimensional (3D) case, the positive magnetoresistance is expressed by[12]

$$\ln[R(H)/R_0]=t_3(e^2a/\hbar^2)r^3H^2, \tag{4}$$

where $R(H)$ is the resistance at a magnetic field of H, e is the elementary charge, h the Planck constant and t_3 the parameter. The parameter t_3 is estimated to be $N_{p3}/24\pi=0.036$ ($N_{p3}=2.7$), where N_{p3} is the threshold value of the mean number of bonds per site in the 3D case.[12] It is necessary to derive the expression of magnetoresistance in 1D cases. The same relationship can be obtained in the case of 1D hopping conduction by expanding the 3D model,[12] as mentioned below.

Under the magnetic field applied to the z direction, the envelope wave function of a localized state $F(r)$ in the Coulomb field is given by[12]

$$F(r)\propto\exp[-r/a_B-l^2ra/(24\lambda^4)], \tag{5a}$$

$$\lambda=(\hbar/eH)^{1/2}, \tag{5b}$$

where $l^2=x^2+y^2$, and a_B is the effective Bohr radius which is consistent with the localization length a in Sec. III A. In the following discussion, symbol a is used instead of a_B. The resistance between two localized states $R'(H)$ is given by:

$$R'(H)=R'_0\exp(\xi), \tag{6a}$$

$$\xi=-2r/a-l^2ra/(12\lambda^4). \tag{6b}$$

In the following discussion, the condition $a\ll l\ll\lambda^2/a$ is assumed, which is consistent with estimated values in the following analysis. Since the second term of Eq. (6b) is as small as $\delta=(ra/\lambda^2)\ll1$, squaring both sides of Eq. (6b) and discarding the term δ^2, we obtain the equation of an ellipsoid:

$$z^2/A^2+l^2/C^2=1, \tag{7a}$$

where

$$A=a\xi/2$$

and

$$C=a\xi/2[1-a^4\xi^2/(96\lambda^4)]. \tag{7b}$$

In order to obtain Eqs. (7a) and (7b), r^2 in the term of first order in δ is replaced with $(a\xi)/2$.[12] In the percolation approach, the percolation threshold ξ_c to form conductive networks can be obtained by solving the equation:

$$N_p=V_\xi\cdot N, \tag{8}$$

where V_ξ is the volume of the ellipsoid of a site, and N the density of sites.[12] In the 3D case, V_ξ and N_p are $(4\pi/3)AC^2$, and N_{p3}, respectively. In order to obtain the form of the 1D case, a 1D array of sites is assumed and N is the 1D density of sites. In addition, V_ξ and N_p are replaced to $2C$ and N_{p1}, respectively. By solving Eq. (8) for the 1D case, ξ_c shows magnetic field dependence of $N_{p1}^3a/(96\lambda^4N^3)$. By substituting ξ_c into Eq. (6b), the following equation is obtained for the 1D case:

TABLE III. Estimated values of a, r and ρ_F at 4.2 K.

Sample	A	B	C
a (nm)	2.2	1.6	1.9
r (nm)	8.0	9.2	8.7
ρ_F (cm^{-1} eV^{-1})	2.2×10^9	1.2×10^9	1.6×10^9

$$\ln[R(H)/R_0]=t_1(e^2a/\hbar^2)r^3H^2,\qquad t_1=N_{p1}^3/96, \tag{9}$$

which has same form as Eq. (4) except for t.

By using Eqs. (3) and (9), the values of r/a and ar^3 are obtained experimentally and the localization length a and hopping distance r can be estimated. The density of localized states ρ_F is also obtained by using Eq. (2). The estimated values of a, r and ρ_F are summarized in Table III. The results show that the localization length and hopping distance are about 2 and 8–9 nm, respectively. There have been several reports on the localized states in the amorphous semiconductor systems.[14,15] Those reports have indicated that the localization length is about 0.1–1 nm and the hopping distance is about 10 nm. The localization lengths obtained in this work are very close to the effective Bohr radii of light and heavy holes bounded by Ga impurities in Si, 1.8 and 1.0 nm, respectively. The hopping distance is comparable to a distance between activated Ga atoms which is estimated from the ion implantation and annealing condition to be on the order of 10 nm. The appearance of 1D-VRH conduction suggests that the effective diameter of the conductive region is comparable to the hopping distance, which means that the effective wire diameter is expected to be less than a few tens of nanometers. Therefore, it can be concluded that the carrier confinement in the nano-size region is achieved for these samples.

The estimated density of localized states, ρ_F, at the Fermi level are about 10^9 cm^{-1} eV^{-1}. A ratio of ρ_F between samples A and B is close to that of the implanted ion doses, which also supports the validity of the analysis in this work. It is difficult to estimate the number density of localized states, because the energy distribution of the density-of-states cannot be evaluated. However, if the effective bandwidth is assumed to be on the order of thermal energy, the number density of localized states is estimated to be about 10^7 cm^{-1}. This value is about ten times smaller than the electrically activated Ga impurity atoms, since the activation efficiency of Ga atoms in Si substrates has been about 5% at an annealing temperature of 690 °C.[6] This fact also suggests that the electrical conductive region is a part of the ion implanted region. Further investigation is necessary to understand the density-of-states of localized states formed in p-Si wires.

IV. CONCLUSIONS

The 1D-VRH conduction in p-Si wires fabricated by selective ion implantation using FIB in n-Si(100) substrates has been investigated. The ion implantation doses and annealing temperatures are changed in the range of $3.5 \times 10^9 - 5.6 \times 10^9$ cm^{-1} at 600–690 °C, respectively. The temperature dependence of wire conductance has the relation of $\sigma \propto \exp[-(T_0/T)^{1/2}]$ below 50 K. The negative and positive magnetoresistance are observed at 4.2 K for weak and strong magnetic fields, which showed the relationships of $R(H)/R_0 \propto \exp(-\beta H)$ and $R(H)/R_0 \propto \exp(\alpha H^2)$, respectively. Both magnetoresistances are considered to be the characteristic feature of hopping conduction. In this work, the positive magnetoresistance of 1D hopping systems is investigated by expanding a 3D model. From the analysis of 1D-VRH conduction, the localization length and hopping distance are estimated to be about 2 and 8–9 nm, respectively. The results suggest that the diameter of the conductive regions in wires is less than a few tens of nanometers. The densities of localized states are $1.2 \times 10^9 - 2.2 \times 10^9$ cm^{-1} eV^{-1}.

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