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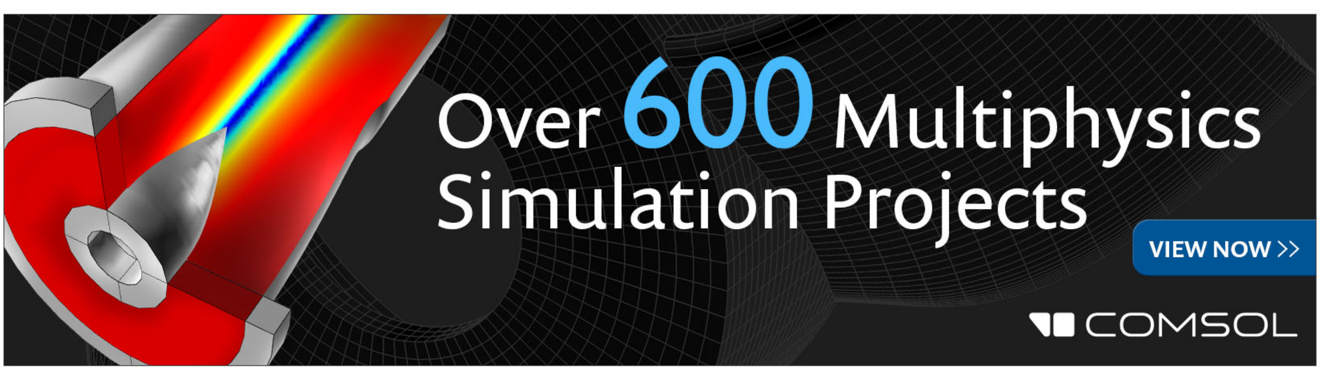

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HTML ABSTRACT + LINKS

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Signatures of quantum transport in self-assembled epitaxial nickel silicide nanowires

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We have measured the electrical properties of self-assembled epitaxial $NiSi_2$ nanowires (NWs) formed on Si substrates. We find quantum corrections due to weak antilocalization and electron–electron interactions. Analysis of the magnetoresistance indicates that electron phase coherence in the NWs is limited by Nyquist dephasing below 10 K, and by electron–phonon scattering at higher temperatures. The phase-breaking and spin–orbit scattering lengths are found to be $\sim$45 nm and 3–7 nm, at 4.2 K, respectively, similar to reports for thin $NiSi_2$ films. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1769583]

There are many barriers to the continued downscaling of microelectronic devices. A bottom-up approach to fabrication, based on self-assembling nanostructures, may offer a solution to these problems. In this regard, recent work on self-assembled epitaxial silicide nanowires (NWs) on silicon has attracted much interest.[1–10] NW formation was discovered for $DySi_2$, [1] and later found for several rare-earth and transition metals. [4–10] These structures may ultimately have practical uses as nanoscale interconnects, sensor elements, or as active devices, in analogy with carbon nanotubes.[11–13] Silicide NWs offer unique advantages over other NW systems; since they are perfect single crystals and are highly compatible with silicon processing. In this letter, we present transport measurements of such epitaxial NWs. Their electrical properties are reminiscent of "dirty metals" and show pronounced quantum corrections due to weak-antilocalization (WAL) and electron–electron interactions (EEI). An analysis of these features allows us to determine the critical length scales for electron transport in the NWs.

$NiSi_2$ NWs were formed on *n*-type Si(111) substrates (10 Ω cm) miscut 8° in the [112] direction. Growth was performed in an ultrahigh vacuum chamber, after flashing the substrate for 30 s at 1250 °C. Ni was deposited at a rate of 1 monolayer every 2 min, and Joule heating was used to maintain the substrate at 500 °C during this process. Growth results in NWs with typical dimensions of 5 nm thick, 15 nm wide, and 1.5 μm long. A transmission electron microscope (TEM) cross-sectional micrograph of one NW is shown in the upper part of Fig. 1 and reveals a nearly perfect crystalline structure.

Two-terminal contacts to the NWs were formed by electron-beam lithography and liftoff (Fig. 1). Prior to metal deposition (Ni/Au:50/200 Å), native oxide at the NW-contact areas was removed by an HF-acid dip. We focus on studies of two NWs (labeled NW1 and NW2), whose dimensions (Table I) were determined by atomic force microscopy (AFM) and TEM. We have also made four-terminal contact pads, but these were bridged by several parallel NWs. These measurements nonetheless allowed us to infer a contact resistance of 1.5 kΩ to each NW, much smaller than the total resistance (Table I). The resistance between contacts unbridged by NWs exceeded 10 MΩ at 4.2 K. Constant cur-

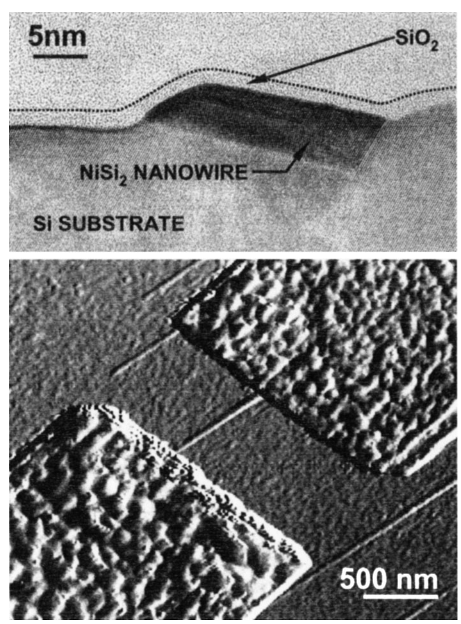

FIG. 1. Upper panel: TEM cross-sectional micrograph of a $NiSi_2$ NW. Lower panel: AFM image of NW1 and its two electrodes.

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TABLE I. Parameters of the two NWs studied here.

Wire	L (nm)	W (nm)	t (nm)	l_{so} (nm)	D ($cm^2 s^{-1}$)	$\mu_{@30\ K}$ (cm^2/Vs)	$R_{@4\ K}$ (kΩ)	$R_{@30\ K}$ (kΩ)
NW1	790	22	6	7.2	0.7	54	51	49
NW2	740	14	6	3.5	0.8	53	71	66

rents (~50 nA) and lock-in detection (11 Hz) were used to measure the NW magnetoresistance (MR) in a variable-temperature insert.

Figure 2 shows the MR of NW1 at several temperatures [each curve has been normalized to its zero-field resistance, $R(0)$]. A positive MR is seen in all traces, and its magnitude increases with decreasing temperature. This behavior is reminiscent of WAL, and very similar MR curves were obtained in studies of NW2. In one-dimension (1D), WAL gives rise to a MR: [14,15]

$$\frac{\Delta R}{R} = \frac{R}{LR_T}\left[\frac{3}{2}\left(\frac{1}{l_\varphi^2}+\frac{4}{3}\frac{1}{l_{so}^2}+\frac{1}{l_h^2}\right)^{-1/2} - \frac{1}{2}\left(\frac{1}{l_\varphi^2}+\frac{1}{l_h^2}\right)^{-1/2}\right]. \tag{1}$$

Here, L is the wire length, $R_T=\sqrt{8}\pi\hbar^2/e^2$, $l_\varphi=(D\tau_\varphi)^{0.5}$ is the phase-breaking length, τ_φ is the phase-breaking time, and D is the diffusion constant. $l_{so}=(D\tau_{so})^{0.5}$ is the spin–orbit scattering length, and τ_{so} is the spin–orbit scattering time. $l_h=(D\tau_h)^{0.5}$ is related to the magnetic field by $D\tau_h=3\hbar^2/e^2AB^2$, where A is the cross-sectional area of the wire and B is the magnetic field applied normal to its plane. $A=W\times t$, where W is the width of the wire and t is its thickness, which we take here to be 6 nm from TEM studies. The solid lines through the lower three data sets of Fig. 2 are single-parameter fits to the form of Eq. (1), which were obtained in the following way. First, we performed three-parameter (W, l_{so}, l_φ) fits of the MR to Eq. (1). As expected, the values of W and l_{so} obtained in this way were insensitive to temperature, and our estimate for W was in good agreement with that obtained from AFM studies. The spin–orbit scattering lengths inferred for the NWs are listed in Table I, and are consistent with studies of epitaxial $NiSi_2$ films (l_{so} ~ 19 nm).[16] With W and l_{so} established in this way, we then performed the "quasi-one-parameter" fits shown in Fig. 2, using l_φ as the fit parameter.

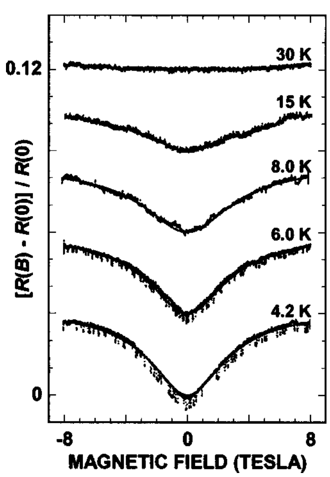

FIG. 2. Temperature-dependent MR of NW1. Successive curves are shifted up from each other by 0.03. Solid lines are one-parameter (l_φ) fits to Eq. (1).

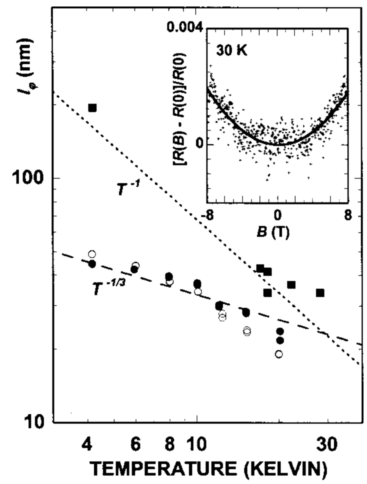

FIG. 3. Temperature dependence of l_φ. Filled circles: NW1. Open circles: NW2. Filled squares: Results (from Ref. 16) Inset: MR of wire NW1 at 30 K. Solid line is a fit to the form $R(B)\propto B^2$.

We have also attempted to fit the MR using the form for WAL in two-dimensions (2D).[14] For NW1, the 2D form fits the experiment well at 15 and 20 K, using the same values of W and l_{so} listed in Table I (see, for example, the data for 20 K in the right-hand side inset to Fig. 4). At lower temperatures, however, reasonable 2D fits can only be obtained by allowing W to vary significantly from its physical value. The suggestion, therefore, is that this NW exhibits a crossover from 1D to 2D WAL, which is consistent with the associated variation of l_φ with temperature. Figure 3 shows that, in NW1, l_φ becomes comparable to W when the temperature is increased to ~20 K. In NW2, the MR is well described by Eq. (1) over the entire range of temperature, and we attribute the absence of a 1D–2D crossover in this NW to its smaller width (~14 nm).

The data of Fig. 2 show a clear suppression of quantum coherence with increasing temperature. At 30 K, the MR shows the classical form $\Delta R(B)/R(0)=(\mu B)^2$, where μ is the mobility (see Fig. 3, inset). By fitting the MR to this form, we infer the wire mobility, and in Table I we list the values of μ for the two wires. These values are much smaller than those quoted for crystalline metals at low temperatures, and are more reminiscent instead of metallic alloys.[17]

In Fig. 3, we plot the temperature dependence of l_φ for NW1 and NW2 and see that the two sets of data fall almost on top of each other. We also plot the variation of this parameter, reported previously for epitaxial $NiSi_2$ films.[16] These data follow the T^1 dependence predicted[18] for electron–phonon scattering, and the variation of l_φ in the NWs appears consistent with this effect above 10 K. At lower temperatures, however, l_φ varies as $T^{1/3}$, as expected for Nyquist dephasing in 1D:[19]

$$\tau_N = \left[\frac{\nu(E_F)\sigma A^2\hbar^4}{2\ e^2 k_B^2}\right] T^{-2/3}. \tag{2}$$

Here, $\nu(E_F)$ is the density of states at the Fermi level and σ is the conductivity. From the $T^{1/3}$ variation in Fig. 3, and with the value of D listed for NW1 in Table I, we use Eq. (2) to infer $\nu(E_F)=3.5\times10^{47}\ J^{-1}\ m^{-3}$. This is consistent with the estimate $\nu(E_F)=7.0\times10^{46}\ J^{-1}\ m^{-3}$, obtained by direct application of the relation $\sigma=\nu(E_F)e^2D$. It also agrees well with

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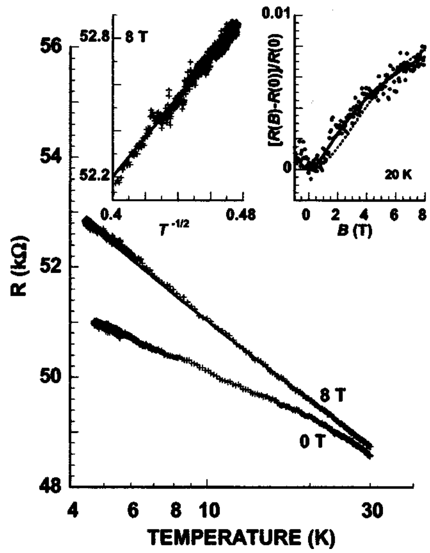

FIG. 4. Main panel: $R(T)$ for NW1 at 0 and 8 T. Solid line through the 8 T data is a one-parameter fit (λ) to Eq. (3). Left inset: 8 T data in the range from 4–7 K, as a function of $T^{1/2}$. Solid line is a one-parameter (D) fit to Eq. (4). Right inset: MR of NW1 at 20 K. Solid (dotted) line is a fit to the two-dimensional (one-dimensional) WAL MR. The (two-dimensional) fit gives better agreement.

$\nu(E_F) = \sim 10^{47}\ \mathrm{J^{-1}m^{-3}}$, calculated for a free-electron system with a Fermi energy of 5 eV.

Figure 4 shows the temperature dependence of the resistance of NW1 at $B=0$ and 8 T. At 8 T, the resistance closely follows a logarithmic temperature dependence. Since this magnetic field should be sufficient to quench WAL, the logarithmic variation is suggestive of 2D EEI. The solid line through the 8 T data is a one-parameter (λ) fit to the theory of EEI in 2D:[20,21]

$$\frac{R(T)-R(T_o)}{R(T_o)} = -\frac{e^2}{2\pi^2\hbar}\lambda R(T)\ln\left(\frac{T}{T_o}\right). \tag{3}$$

Here, λ is a constant $(0 \leqslant \lambda \leqslant 1)$ describing the effects of Coulomb screening and T_o is an arbitrary reference temperature. From the 8 T data in Fig. 4, we infer $\lambda=0.067$, within the range expected from theory. At 0 T, the resistance variation deviates from a $\ln T$ dependence below 20 K, as the WAL comes into play as we have discussed already.

Below $\sim$7 K, the resistance at 8 T in both NWs appears to follow the $T^{1/2}$ dependence predicted for EE1 in 1D (Fig. 4, left-hand side inset):[20,21]

$$\frac{R(T)-R(T_o)}{R(T_o)} = \frac{e^2}{2\hbar}\frac{R(T)}{L}L_T, \quad L_T = \sqrt{\frac{\hbar D}{k_B T}}. \tag{4}$$

Equation (4) valid at temperatures for which W is less than the thermal length L_T. By fitting the low-temperature resistance variation to Eq. (4), we can estimate the diffusion constant in the two NWs. Our results are listed in Table I and imply a thermal diffusion length of $\sim$12 nm at 4.2 K, comparable to the width of the NWs. It therefore seems plausible that, at the lowest temperatures, the signature of 1D EE1 should be observed in the resistance.

It is interesting to compare the properties of these NWs to those of bulk and thin-film silicides. Resistivities of $<1\ \mu\Omega$ cm have been reported for high-purity bulk crystals of $CoSi_2$,[22] while $\sim$60 $\mu\Omega$ cm has been reported for 3 nm thick $NiSi_2$ films.[16] von Kanel measured the systematic influence of film thickness on surface scattering and found a surface resistivity of 100 $\mu\Omega$ cm in 1 nm thick $CoSi_2$ films. Our NWs have resistivities of $\sim$800 $\mu\Omega$ cm and we believe that this is due to *interface* scattering due to native oxide at the free NW surface, which may be reduced by passivation. Indeed, Lee *et al.*[23] have studied *free-standing* $NiSi_2/C$ composite NWs and obtained 350 $\mu\Omega$ cm at 4.2 K.

To conclude, we have presented transport measurements of epitaxial silicide NWs. Electron coherence is limited by Nyquist dephasing below 10 K, and by electron–phonon scattering at higher temperatures. The phase-breaking and spin–orbit scattering lengths are found to be comparable to those in thin $NiSi_2$ films, although the nanoscale dimensions of the NWs allow the observation of quantum transport at high temperatures (at least 30 K).

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