Newly Observed Phase Coherent Electron Transport Properties in the Mesoscopic Loop Structure of Aluminum Wire

Seongjae Lee, Kyoung Wan Park, Mincheol Shin, El Hang Lee, JuJin Kim and Hu Jong Lee

CONTENTS

ABSTRACT

We have identified two new features related to the coherent transport in the mesoscopic loop structure of aluminum wire, including the autocorrelation of the conductance fluctuations beyond B_c and fine structure in the low-field magnetoresistance curve in the superconducting transition regime, which, to the best of our knowledge, have not been reported in the literature. Since the electrons in Al have a phase coherence length larger than 1 μm at or below $T = 3$ K, which is comparable to the dimensions of the structure, the wave nature of the electronic transport has been clearly observed: the universal conductance fluctuations, the Aharonov-Bohm oscillations, and the Altshuler-Aronov-Spivak oscillations. Due to the transition of Al to a superconducting state at $T = 1.3$ K, the coherent phenomena of Cooper pairs, i.e., the Little-Parks oscillations, have also been observed.

I. INTRODUCTION

The quantum transport in mesoscopic systems has been of intensive interest for more than a decade [1]. Due to the recent advancement of ultrafine lithographic techniques, mesoscopic structures have become readily available in such a way as to maintain the electron's phase coherence throughout a whole sample at low temperatures, which is required for the manifestation of the quantum mechanical nature of electrons. Some of the interesting features of electronic transport discovered in the mesoscopic structures of metals include: the universal conductance fluctuations [2], the Aharonov-Bohm (AB) oscillations [3], nonlocality of the resistance [4], and the Coulomb blockade effect [5].

The other system where long range phase coherence is maintained is a superconductor although it attracts less attention recently. The phase coherence in a superconductor which persists over a macroscopic scale is due to the condensation of Cooper pairs. Several theoretical investigations of superconducting mesoscopic structures have been carried out in a similar manner to those of the normal metals [6]. Recently Petrashov, et al. [7] reported a two-fold enhancement of the Aharonov-Bohm oscillations in the coupled structure of mesoscopic Ag ring with Pb-Au alloy superconducting contacts, which cannot be anticipated by existing theories.

In this paper, we report the coherent electron transport phenomena in an Al mesoscopic structure containing a loop. Al is chosen because it has a relatively long inelastic scattering length suitable for the present study and it undergoes a superconducting transition near 1.2K, which makes it a good candidate for the study of superconducting mesoscopic systems.

II. EXPERIMENTAL

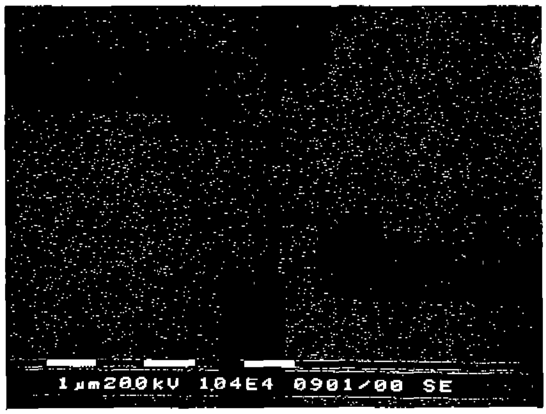

Fig. 1. SEM micrograph of a mesoscopic structure containing a square loop, $0.9 \times 0.9 \mu m^2$, and connecting leads with $0.2 \mu m$ line width.

A square loop of outer size about $0.9 \times 0.9 \mu m^2$ with $0.2 \mu m$ linewidth and the connecting leads were patterned using electron beam lithography on a polymethyl methacrylate (PMMA) (400nm) / SiO_2 (90nm) / Si-wafer as shown in Fig. 1. The SiO_2 layer was etched with buffered oxide etchant(BOE) for an overhang structure after an opening in the PMMA was made. A 20 nm thick Al film was then deposited by thermal evaporation in a vacuum of 1×10^{-6} Torr, which is then followed by a lift-off process.

For measurements, we have adopted a four-terminal ac bridge circuit consisting of a lock-in amplifier, operating at 33 Hz, and two differential preamplifiers. In order to protect the sample from an accidental discharge, we connected an $1k\Omega$ resistor at each electrical lead. The sheet resistance of the film at 4.2K is about 1.77Ω and the resistance ratio R(300K) / R(4.2K) is 2.08.

III. RESULTS AND DISCUSSION

The Al structure shows a typical resistive transition to a zero-resistance state at temperatures below 1.3K as displayed in Fig. 2, which was taken with a current of 10μA. This $R(T)$-curve, however, has a rather peculiar looking resistive peak near the superconducting fluctuation regime. It is a unique characteristic found only in mesoscopic superconducting structures to date. Recently, much attention has been paid to this anomalous resistive peak [8], but it still evades a proper explanation. We believe that the resistance anomaly is not one of the usual class of the quantum interference phenomena associated with normal electrons in solids. We have evidence that the superconductivity plays an important role. Details will be presented separately.

Magnetoresistance curves for the magnetic field interval ($-150 \sim +150$ gauss) at various temperatures ranging from 3.50K to 1.157K

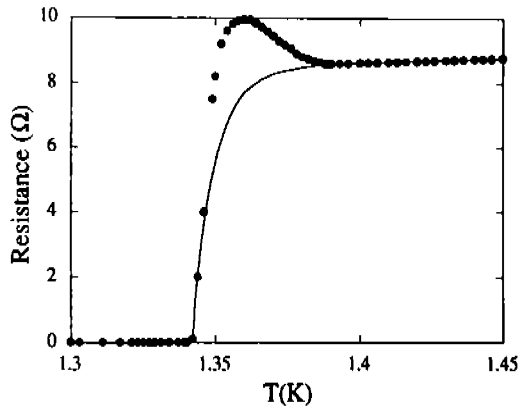

Fig. 2. Resistance as a function of temperature, which shows a superconducting transition with anomalous resistance peak. Filled circles represent data and a solid line a deduced normal resistive curve without the anomaly.

are shown in Fig. 3. Periodic structures corresponding to the flux quantization in the units of the flux quantum $(h/2e)$, associated with a multiply connected geometry (closed loop structure shown in Fig. 1), are clearly seen. Although they have the same periodicity, the mechanisms leading to the oscillations are quite different for the temperature regions above and below the superconducting temperature, $T_c(= 1.36\text{K})$. Above T_c, the oscillations arise from the same phase coherent paths that cause the weak localization of the electrons at low temperatures [9]. The interference contribution to the current of the electrons following two time-reversed paths encircling flux through the square loop (clockwise and counterclockwise) results in the oscillations in resistance as B varies; the Altshuler-

Aronov-Spivak (AAS) oscillations. Because of the formal resemblance to the Cooper pairs, such time-reversed paths are called "Cooperons". Since the time-reversed paths encircle twice the flux through the loop area (2Φ), i.e., one for each, the resistance of such a system oscillates with a period of $h/2e$. However, the oscillations decay rapidly with increasing magnetic field, because the magnetic field destroys the time-reversal symmetry. For fields greater than $B_0 = (h/e)/A_l$, where A_l is the area of the metal coverage of the loop, many sets of Cooperons are significantly out of phase and the sum of their contributions averages to zero. In our sample, $A_l = 0.56\mu\text{m}^2$ due to 0.2μm width, and $B_0 = 70$ gauss, which is consistent with our data.

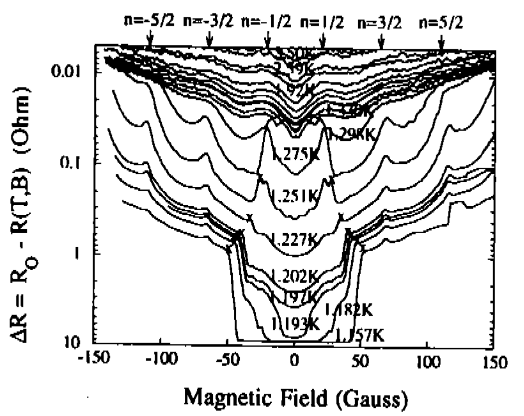

Fig. 3. Magnetoresistance curves taken at various temperatures. n indicates the magnetic field corresponding to a magnetic flux of $\phi = n\phi_o$, where ϕ_o is a flux quantum, $h/2e$.

Below T_c, the superconducting square loop in a magnetic field tends to quantize the magnetic flux threaded through the loop. The quantization occurs because the wave function for the Cooper pairs is quite rigid, i.e., in order to satisfy the 2π gauge symmetry as the wave function encircles the loop, the flux through it must precisely satisfy the condition, $\Phi = n(h/2e)$; where n is an integer and the extra factor of 2 appears because the Cooper pairs carry charge $2e$. This flux quantization also leads to an oscillation in T_c and also in the resistance, which is called the "Little-Parks (LP) oscillation" [10]. From the data, we can extract the effective area of the loop; $S = (h/2e)/\Delta B = (0.69\mu m)^2$ where ΔB is measured to be 44 gauss from Fig. 3. This value is in good agreement with the value of the physical area estimated from the scanning electron microscope (SEM) picture, where the area closed by the center line of the loop is $\sim (0.7\mu\text{m})^2$.

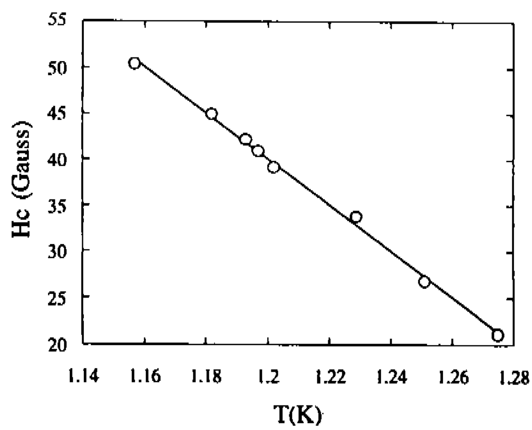

Fig. 4. Critical field vs. temperature.

As the temperature is lowered, a smooth

crossover from AAS to LP oscillations is observed although they have different origins. The resistance anomaly mentioned earlier manifests itself as a considerable disturbance in a narrow window both for the magnetic field and the temperature of $-15 < B < +15$ gauss and $T_c - 0.05\text{K} < T < T_c + 0.05\text{K}$, respectively. As the temperature decreases, the superconducting critical field can be clearly defined as marked by "x" in Fig. 3. We plotted the critical field versus temperature in Fig. 4. If we fit the curve to the standard relation,

$$H_c(T) = H_0[1-(T/T_c)^2]$$
$$\sim 2H_0(1-T/T_c) \qquad \text{for near } T_c,$$

we obtain $H_0 = 170$ gauss and $T_c = 1.360\text{K}$. These values are greater than those for the bulk $A_l : H_c^{\text{bulk}} = 105$ gauss and $T_c^{\text{bulk}} = 1.14\text{K}$, as listed in Table 1.

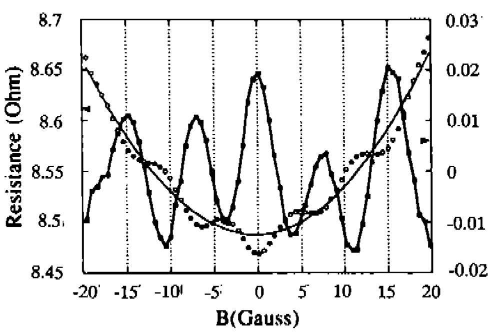

Fig. 5. Magnetoresistance for low fields at $1.251K$ (denoted by circles) shows small oscillations. To emphasize the feature, the parabolic background (denoted by a line) has been subtracted and the results are represented by squares with cross.

One interesting feature of Fig. 3 is the fine structures that can be seen between fields

Table 1. Material parameters for properties of aluminum (bulk).

Normal properties

electron density (n)	$1.81 \times 10^{23}\text{cm}^{-3}$
Fermi velocity (v_F)	$2.03 \times 10^{8}\text{cm sec}^{-1}$
resistivity (ρ)	$2.45 \times 10^{-6}\Omega\text{cm}$ (at 273K)
transport scattering time	$0.80 \times 10^{-14}\text{sec}$ (at 273K)

Superconducting Properties

transition temperature (T_c)	1.14K
coherence length (x)	1.6μm
penetration depth (l)	0.016μm
critical field (H_c)	10^5 gauss

corresponding to the flux, $+\phi_o/2$ and $-\phi_o/2$ ($\phi_o = h/2e$) in the temperature range of $T = 1.275 \sim 1.193\text{K}$. The most prominent structure can be seen at $T = 1.251\text{K}$. If we subtract a parabolic background as in Fig. 5, a periodic structure with the period of $\phi_o/6$ can be distinctively recognized. However, the periodicity varies with temperature and seems to have no explicit relation with respect to a given temperature. A careful examination reveals that this fine structure appears across the entire range of magnetic field shown in Fig. 3. We have no explanations as to the cause of this interesting phenomena. To the best of our knowledge, such a fine periodic structure with a period less than one flux quantum, ϕ_o, in a superconductor has never been proposed, or observed before. Since it occurs in the superconducting transition regime, just before the onset of global phase coherence of the superconducting order parameter, we speculate the effect involves an interference of the order parameter fluctuations, which needs further investigations.

Table 2. Values of the parameters used in the fit to the magnetoresistance data of the loop.

$T(K)$	$R_o(\Omega)$	$\beta(T)$	$L_i(\mu m)$	$L_{so}(\mu m)$
1.410	8.808	3.44	1.33	0.52
1.608	8.820	2.07	1.30	0.52
1.730	8.823	1.91	1.25	0.52
1.917	8.828	1.55	1.20	0.52
2.350	8.834	1.10	1.09	0.52
3.50	8.84	0.95	0.78	0.52

* R_0 : the normal-state resistance at $B = 0$

$\beta(T)$: electron-electron interaction strength parameter, represents the superconducting fluctuation which diverges at T_c

L_i, L_{so} : inelastic and spin-orbit scattering length.

See [9] and [12] for details.

Note the large values of L_i.

The AAS oscillations have been well-studied along with the weak localization phenomena [11]. Thus we can use our magnetoresistance data above T_c to extract various parameters of the electronic transport, especially the inelastic scattering length, which is a key parameter characterizing a mesoscopic system. Our data and the fitting to the weak localization theory [12], [13] are shown in Fig. 6, and in Table 2 we listed the values of the parameters determined from the fitting. The inelastic scattering length is closely related to the electron's phase coherence length. The breaking of the wave-function phase memory requires a change of its energy state; the changes of the momentum direction from impurity scattering are not sufficient. In the absence of magnetic impurities, the inelastic scattering length is just the electron's phase coherence length. From the table, the inelastic scattering length ranges from 0.78μm at $T = 3.50$K to 1.33μm at $T = 1.41$K, while the elastic scattering length (mean free path) remains almost constant to be 0.016μm determined from the resistance. Note that the inelastic scattering length of 1.33μm at 1.41K is sufficiently close to the whole dimension of the square loop system, which qualifies our system as a mesoscopic one. The usual temperature dependence of the inelastic scattering length is known to be proportional to T^{-p} ($1/3 < p < 3$, depending on the relaxation mechanism, where $p = 1/3$ corresponds to 1D electron-electron scattering mechanism [14]) and we find $p \sim 0.4$ for our data.

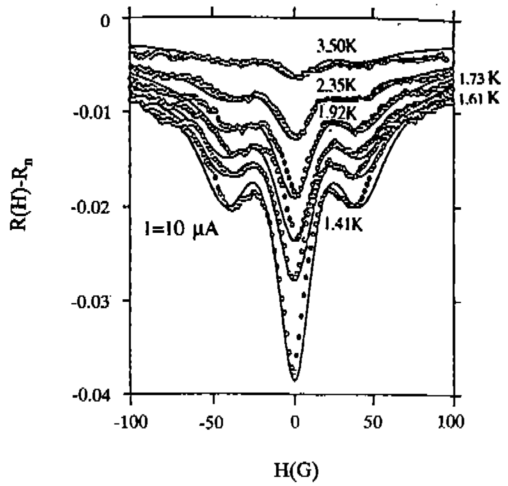

Fig. 6. Oscillations of the magnetoresistance due to the coherent normal electrons in the loop at various temperatures. The solid lines represent fits to the weak localization theory. See [9] and [12] for details.

One of the properties of the coherent transport is the universal conductance fluctuation [15]. The fluctuation arises from the quantum mechanical interferences among various trajectories that the electrons follow as they migrate from one end of the sample to the other. In the case of a magnetic field sweep, the random tangle of paths through the sample will generate different interference patterns depending on the amount of flux threaded among the paths. Therefore, each fluctuation pattern corresponds to one specific impurity configuration. As the magnetic field increases by some correlation field, B_c, conductance fluctuates randomly by $\sim e^2/h$. Reproducible

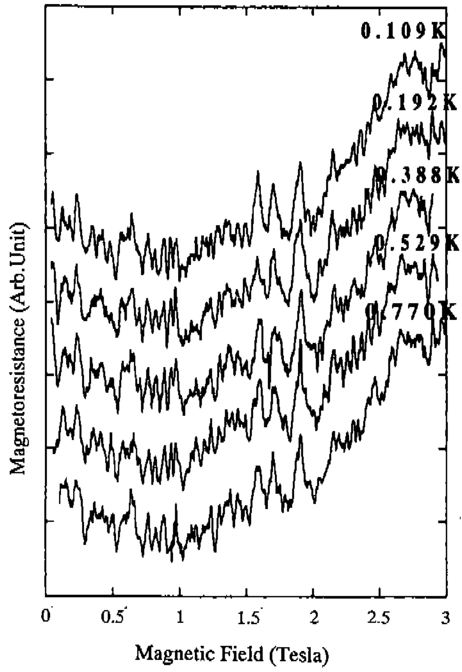

Fig. 7. Conductance fluctuation data taken at temperatures 0.109, 0.192, 0.388, 0.529, 0.770K. Each curve is vertically offset for clear viewing.

magnetoresistance data at various temperatures (0.770K $\sim$ 0.109K) for a magnetic field up to $3T$ are plotted in Fig. 7. Since the zero temperature superconducting critical field is 170 gauss, superconductivity is quenched above the critical field, leaving only the normal electron's effect exhibited in the figure. The magnetoresistance fluctuation data clearly exhibit a nearly identical pattern for all temperatures less than 0.770K within 90%. This observation is consistent with the fact that the phase coherence length is comparable to the distance between the voltage probes for the temperature range explored, so that most of the inelastic scatterings occur in the reservoirs at the ends of the sample. Also it implies that changes in impurity configurations for all runs are minor, because the fluctuation pattern is so critically dependent on the impurity potentials that the motion of so much as one impurity by more than an electron's Fermi wavelength (a few Angstrom) can completely rewrite the patterns.

The root-mean-square conductance fluctuation, $\Delta g = [\langle g^2\rangle - \langle g\rangle^2]^{1/2}$, is calculated and we obtain $\Delta g = (0.118 \sim 0.127)e^2/h$ for the temperatures in Fig. 7. These values are rather small compared to the theoretically predicted value, Ce^2/h, with C being a constant of order of unity or a reported value of $0.3e^2/h$ for Au wires [16] . One of the possibility for the reduction is the many-body effect of the ensemble averaging due to the broadening of the electron's energy distribution by $k_B T$. Two electrons with energies differing by more than the correlation energy, E_c ($= \hbar D/L_\phi^2$, where D is the diffusion constant and L_ϕ is the phase coherence length), execute uncorrelated motions after a diffusion of a distance L_ϕ [17]. Temperatures larger than E_c smear the Fermi distribution so that electrons at different energies contribute uncorrelated patterns to the fluctuations and the number of the patterns is $N \sim k_B T/E_c$. When $N > 1$, $\Delta g = CN^{-1/2}e^2/h$ and when $N < 1$, $\Delta g = Ce^2/h$. In Fig. 7, the temperature dependence of the magnitude of Δg is nearly absent, suggesting $E_c > k_B T$. E_c can be calculated to be 3.5×10^{-5}eV using $D = 140$ cm^2/sec and $L_\phi = 1.3\mu$m and it is smaller than $k_B T = 6.7 \times 10^{-5}$eV for $T = 0.770$K. These are contradictory results and need further study both theoretically and experimentally. Another possibility is the ensemble averaging due to the energy distribution caused by a bias voltage, ΔV, which is 88μV for a good signal-to-noise ratio. The energy distribution of the conducting electrons, $e\Delta V = 8.8 \times 10^{-5}$eV, is greater than E_c, resulting in the reduction of Δg by the factor of $[E_c/(e\Delta V)]^{1/2} \sim 0.63$.

Magnetoresistance data taken with opposite directions of the magnetic field are shown in Fig. 8. The fluctuation is superimposed on a parabolic background, which can be fitted to the classical theory [18] as follows:

$$R(B) = aB^2 + bB + R_o$$

where $a = 0.77 \times 10^{-3}\Omega/T^2$, $b = 1.0 \times 10^{-3}\Omega/T$, and $R_o = 8.8\Omega$. The parabola is not symmetric about $B = 0$ possibly due to the Hall effect. It can be confirmed by the fact that the deduced value of electron density from the effect is roughly 3×10^{23}cm^{-3}, which is comparable to the one listed in Table 1. The quadratic term in B comes from the longitudinal part of the resistance, which is given as $\sim (n_h/n_e)(\omega_c\tau_e)(\omega_c\tau_h)R_0$, where ω_c is the cyclotron frequency and τ_e and τ_h are scattering times for electrons and holes. A rough calculation yields $(n_h/n_e)\tau_e\tau_h \sim 3 \times 10^{-27}$sec^2.

To investigate the correlations of the fluctuations with respect to the magnetic field, we ob-

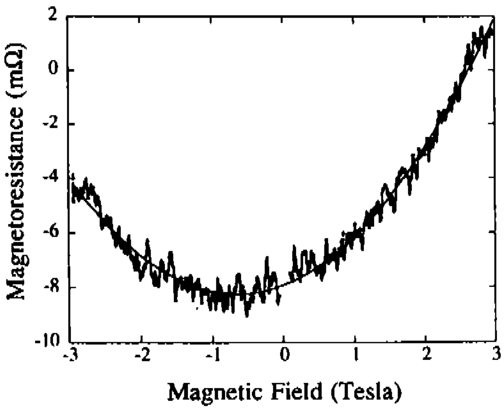

Fig. 8. Magnetoresistance curves at 0.109K, showing the conductance fluctuation on the classical background. See the text.

tain the conductance fluctuation data, $\Delta g(B)$, by subtracting the classical background from the magnetoresistance data and converting it to conductance. The auto-correlation functions, $\langle \Delta g(B) \Delta g(B + \Delta B) \rangle$ that are shown in Fig. 9 for all temperatures, show an initial decay with a nearly identical correlation field, $B_c = 0.023T$, as expected. B_c can be used as a direct measure of the phase coherence length in the metal [15]. Since B_c is given by $\sim (h/e)/wL_\phi$, where w is the width of a wire, L_ϕ turns out to be $\sim 0.9\mu m$. This value is not far from the value $1.3\mu m$ obtained from the weak localization data.

A new feature about Fig. 9 is that there are further correlations after an initial decay, represented by peaks at $B = 0.05T$, $0.11T$, $0.16 \sim 0.17T$, $0.20 \sim 0.21T$. These structures seem to have the periodicity of $0.05T$ and the amplitudes of successive peaks do not diminish significantly. We also note the tails for $T = 0.109$, 0.388, 0.529, and 0.770K, which do not have "baselines" at zero. It does not originate from the Aharonov-Bohm oscillation effect (AB oscillation) [3] due to the presence of the loop geometry between voltage probes, because the area of $0.08\mu\text{m}^2$, corresponding to the periodicity of $0.05T$, is too small for the physical area of the loop. This behavior has never been reported before and its origin is not clear.

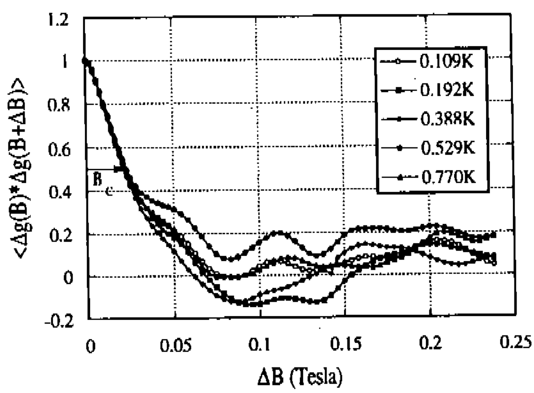

Fig. 9. Auto-correlation function, $\langle \Delta g(B) \Delta g(B + \Delta B) \rangle$ for five temperatures.

The AB oscillation is not pronounced in the magnetoresistance data, but is recognizable in the Fourier-transformed data, as displayed in Fig. 10. The reason for this small amplitude of the AB oscillation is that the ratio of the wire width to the square size is considerable, $0.2\mu\text{m}/0.8\mu\text{m} = 0.25$, so that the sum over oscillations with wide range of frequencies cancels out most of the interference patterns. The

AB oscillation is represented by a group of peaks marked by arrows in Fig. 10, which was taken from the magnetoresistance data at $T = 0.527\text{K}$ for $0 < B < 1.3T$. The period of the oscillation that survives is in agreement with the expectation that $\Delta\Phi = h/e = \Delta B \times$ (area enclosed). The inner and outer lengths of the square measured in the SEM are $0.50\mu\text{m}$ and $0.90\mu\text{m}$, while the calculated ones from the Fourier spectrum are $0.54\mu\text{m}$ and $0.57\mu\text{m}$.

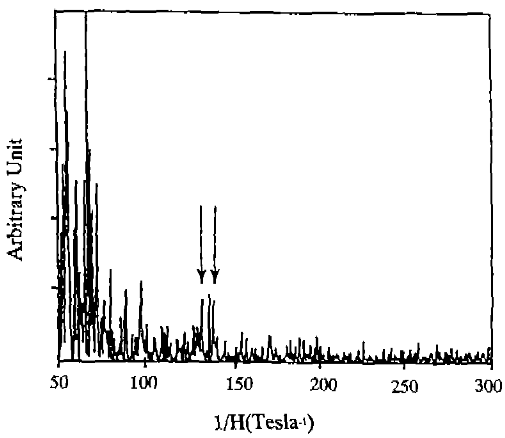

Fig. 10. Fourier spectrum of the magnetoresistance data at $T = 0.527\text{K}$ for $0 < B < 1.3T$. The AB oscillation is represented by a group of peaks marked by arrows.

In conclusion, coherent electron transport phenomena in an Al mesoscopic structure have been investigated. The AAS oscillation, the AB oscillation, the universal conductance fluctuation, and the LP oscillation have all been identified. Two new interesting features have been found: a fine structure in the low-field magnetoresistance curve in the superconducting transition regime and the additional autocorrelation in the conductance fluctuation beyond B_c, which, to the best of our knowledge, has never been reported and needs further systematic studies.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Byung-Sun Park for his enthusiastic effort in the e-beam lithography. This work has been funded by the Korea Telecom and the Ministry of Communications, Korea.

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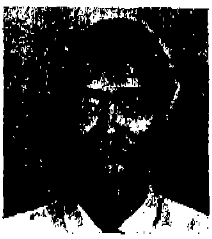
Seongjae Lee was born in Korea in 1957. He received a B.S. degree from Seoul National University in 1980, M.S. degree from Korea Advanced Institute of Science in Seoul, Korea in 1982, and Ph.D. degree in Physics from Northwestern University in Illinois, U.S.A. in 1991. Currently he is working in Research Department in Electronics and Telecommunications Research Institute in Taejon, Korea. His research interests are in the electrical transport of the metallic and superconducting systems with reduced dimensions, the mesoscopic systems of metal or semiconductor and the device applications of the mesoscopic systems.



KyoungWan Park was born in Seoul, Korea in 1956. He received B.S. and M.S. degrees in physics from Seoul National University, Seoul, Korea in 1978 and from Korea Advanced Institute of Science, Seoul, Korea in 1981, respectively, and his Ph. D. degree in physics from North Carolina State University, Raleigh, North Carolina, U.S.A., in 1990.

From 1981 to 1984, he was a researcher with the Optics Laboratory of Korea Standards Research Institute. In 1990, he joined Research Department in ETRI. His research interests include thin film growth of semiconductors, surface treatments and optical measurements on compound semiconductors, and mesoscopic phenomena.

Mincheol Shin was born in Hong Sung, Korea in 1965. He received the B.S. degree in physics from Seoul National University, Seoul, Korea in 1988 and the Ph. D. degree in physics from Northwestern University, Evanston, Illinois, USA in 1992. Since 1993, he has been with Research Department in ETRI working on theoretical modellings and calculations for mesoscopic systems.

El Hang Lee graduated from Seoul National University with a B.S. degree (summa cum laude in Electrical Engineering in 1970, and subsequently received M.S., M. Phil. and Ph.D. degrees in Applied Physics from Yale University in 1973, 1975 and 1978, respectively. Dr. Lee then spent two years (1979–80) with Princeton University as a research fellow, four years (1980–84) with Monsanto Electronic Materials Company as a research scientist, and six years (1984–90) with AT&T Bell Laboratories as a seninor member of technical staff. He has lectured at several universities including Princeton, Seoul National University, Chungnam National University and Korea Advanced Institute of Science and Technology. His research interests include solid-state/semiconductor sciences and lightwave/photonic/optoelectronic sciences. He has published over 100 papers in major international and domestic journals and proceedings and has given a dozen invited talks worldwide. He has been awarded scholarships, fellowships, and outstanding service award, and is cited in Marquis Who's Who and in American Men and Women of Science. He is a member of the American Physical Society, American Association for the Advancement of Science, Optical Society of America, Materials Research Society, SPIE, IEEE/LEOS Society (Senior Member and Chapter Chairman), Korean Physical Society (Fellow), Optical Society of Korea (Fellow and Board Member) Sigma Xi and New York Academy of Sciences. He has served many times as chairman or as a member of international and domestic conference/workshop program committees, organization committees and advisory committees. Dr. Lee is currently serving as Director of Research for Basic and Advanced Technology at ETRI.

Hu Jong Lee was born in Hong Sung, Korea in 1953. He received the B.S. degree in Physics from Seoul National University, Seoul, Korea in 1975 and the Ph.D degree in Physics from Ohio State University, Columbus, Ohio, U.S.A. in 1985. He worked in Agency for Defense Development as a researcher for 1976 - 1979. From 1985 to 1986, he was a research associate with the Physics Department of Ohio State University. From 1986 to 1987 he was with the Physics Department of Harvard University. He joined the Physics Department of Pohang Institute of Science and Technology as a professor in 1987. His research interests include the electrical transport of the disordered metallic or superconducting systems with a reduced dimension and mesoscopic systems, electron localization, vortex dynamics in superconducting films, and the dynamic properties of Josephson junction arrays.

JuJin Kim was born in 1964. He received the B.S. degree in physics from Seoul National University, Seoul, Korea in 1986 and the M.S. degree in experimental condensed matter physics from the same university in 1988, and the Ph.D. degree in experimental condensed matter physics(low temperature physics) from Pohang Institute of Science and Technology, Pohang, Korea in 1993. Since August 1993, he has held a post doctoral position with the Department of Industrial Chemistry of Tokyo University, Japan.