Magneto-Resistance Peaks and Phase Breaking Behaviour in a Thin Multi-Walled Carbon Nanotube

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Abstract. The low temperature magneto-resistance (MR) has been studied in a single thin multi-walled carbon nanotube (MWNT) field effect transistor (FET). The phase coherent properties of electron transport in the FET have been deduced from results of quantum-transport studies. A large zero-field peak is observed in the low-temperature MR, and exhibits superimposed oscillatory components. Phase coherence is discussed, and the carrier concentration is also estimated, by analyzing these results in terms of quantum interference.

1. Introduction
There has been great interest in carbon nano-tubes (CNTs) as a key technology for new device applications, such as nano-scaled transistor for spin electronics, or for various nano-sensors, especially for bio-related applications. Many problems need to be overcome in order to apply these nanotubes to room-temperature quantum devices. In order to develop working CNT devices, it is necessary to determine their device characteristics, such as carrier concentration and mobility. There do not yet exist, however, standard methods for device characterization for CNT electronics. In this study, we apply the low temperature magneto-resistance (MR) as a tool to determine the transport characteristics of CNT FETs. The degree of quantum coherence and the carrier concentration are very important properties and are determined here from the low temperature MR studies.

Quantum interference effects, such as weak localization (WL), the Aharonov Bohm (AB) effect, the Al’tshuler Aronov Spivak (AAS) effect, and universal conductance fluctuations (UCF), have previously been observed in multi-walled carbon nanotubes (MWNTs) [1]. A knowledge of phase breaking effects in coherent transport is very important for the study of these quantum interference phenomena. The temperature (T) dependence of the phase coherence length, $L_{\phi}$, of MWNTs has been reported to follow a power law dependence of $T^{-1/3}$, characteristic of one-dimensional interference [2]. In the case of single walled CNTs, the power low dependence also shows a $T^{1/3}$ dependence [3]. In addition, as further evidence of low dimensional transport, there are some experimental reports of Tomonaga-Luttinger liquid behavior in CNTs [4]. In this study, we analyze phase breaking in the quantum-coherent properties of a thin MWNT by means of low temperature MR measurements.

2. Experiments
Our thin MWNT sample is a high quality one synthesized by arc discharge. The G/D ratio determined by Raman measurement is about 30, indicating that the CNT is almost free of defect contamination.
The diameter of the wire is around 15 nm and has about 10 layers that are determined from TEM observation. For four-terminal resistance measurements, 20 nm thick Pd electrodes were contacted to the MWNT after depositing it onto a SiO$_2$/Si substrate. The heavily doped Si substrate works as the gate electrode for the FET. In comparison to the case of using Ti/Au electrodes, the contact resistance of the Pd is found to be much lower [5]. We fabricated our MWNT samples using AFM manipulation. The fabricated MWNT device is shown in the scanning electron micrograph of Fig. 1 (a). Low temperature MR measurements were performed using a He-3 cryostat and applying perpendicular magnetic field up to 8 T. More detailed experimental procedures are reported elsewhere [6].

![Scanning electron micrograph of the thin MWNT sample. The separation between voltage electrodes is about 3 µm.](image)

(b) The observed low temperature magneto resistance at 0.4 and 14.9 K. A large central peak can be observed, even at higher temperatures, although the small oscillatory peaks are quickly damped with increasing temperature. The magnetic field has been applied perpendicular to the CNT axis.

3. Results and discussions
The low temperature MR of our device is found to exhibit a large and symmetric zero-field peak that shows a weak temperature dependence (Fig. 1 (b)). In contrast, the smaller oscillatory peaks quickly
Figure 2. Oscillatory component obtained by subtraction of the large negative MR peak from the original signal at 0.4 K (Fig. 1(b)). The oscillation period clearly changes around 3 T.

Figure 3. Oscillation components in Fig. 2 are plotted as a function of $B^{-1}$. The high field region of the data, below 0.3 T$^{-1}$, seems to consist of regular oscillations.

Wash out with increasing temperature. The large peak is reminiscent of WL, although its amplitude seems far too large for this. To analyze the oscillatory component, we subtract the large negative MR from the original MR at 0.4 K. This result is shown in Fig. 2, from which it can be seen that the character of the oscillations changes dramatically around 3 T. In Fig. 3, we plot the oscillatory MR component as a function of the inverse of the field. In this figure it can be seen that the higher field component, below 0.3 T$^{-1}$, seems to show a constant period (in $B^{-1}$) of oscillation while the lower field component shows an increasing period. This result indicates that the electron scattering process changes clearly at a threshold field around 3 T. The threshold field is believed to be related to a crossover between two different transport mechanisms. We suggest here that these are AAS oscillations at low field and Shubnikov-de Haas (SdH) oscillations higher fields.

At higher fields, the carrier concentration, $n_s$, can be obtained from the SdH period in a $B^{-1}$ plot, according to

$$\Delta\left(\frac{1}{B}\right) = -\frac{e}{h} \frac{1}{n_s}$$

where $e$ and $h$ are electron charge and Planck constant, respectively. From our experimental data, $n_s$ can estimated to be on the order of $10^{12}$ cm$^{-2}$. At lower fields, where the oscillation period is almost constant, AAS type oscillations are likely responsible. However, in MWNTs, the AAS peak at lower field side has been observed almost only for parallel magnetic field applications [8]. Therefore, we
need more precise MR measurement including studies as a function of the field direction relative to the MWNT axis.

As for the AAS type oscillation component on the low field side, their period exhibits the temperature dependence shown in Fig. 4. Results for two different thermal cycles are shown in this figure and agree reasonably well with each other. In both sets of data, the oscillation period suddenly increases. This likely indicates a decrease of the coherent area at higher temperature because of increased phase breaking. This behavior is almost consistent with the power law dependence in the coherent length as reported in the previous study in MWNT [2].

Figure 4. Peak interval at lower field side, where almost field independent, is plotted as a function of temperature.

4. Summary
We have measured the low temperature MR of a thin MWNT. Small oscillatory components in the MR show evidence of AAS and the SdH oscillations, at the lower and the higher fields, respectively. Based on a simple analysis for the MR, we have estimated the carrier concentration and analyzed the phase breaking in the thin MWNT. With further investigation of the small oscillation peaks, the phase breaking mechanisms in MWNT can be clarified.

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