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Diameter dependence of 1/*f* noise in carbon nanotube field effect transistors using noise spectroscopy

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ABSTRACT

Carbon nanotubes (CNTs) have many interesting properties for nano devices such as high sensitive sensors or noise enhanced nonlinear devices. A field effect transistor (FET) structure is one of the key features for these applications, and the control of noise in FETs is important for the actual operation of the application. Several origins of noise have been proposed, and defects and/or surface adsorption of molecules seem to be dominant for the 1/*f* type noise in CNTs. To study the origins of noise, the diameter dependence of noise properties was studied. We analyzed the noise properties in CNTs using noise spectroscopy with different fabrication parameters or ambient environments. We observed the crossover of noise properties in CNTs, which involved transition between different origins of noise depending on their diameter. Additionally, noise spectroscopy was used to observe such crossover between air and vacuum environments. We can control noise intensity using the gate voltage, and noise properties can be controlled by the fabrication parameters. These phenomena are useful for the stochastic operation of CNT-FETs.

1. Introduction

Nano carbon materials have attracted much interest and several applications have been proposed. Carbon nanotubes (CNTs) [1,2] also have many interesting properties for nano devices and/or building blocks for nano technology. For example, nano-sized transistors, field emission devices, biosensors, and interconnections in large-scale circuits have been developed. Several technologies can be utilized in these applications, such as n-type field effect transistor (FET) fabrication [3]. The room temperature operation of single electron transistors, which can usually work only at low temperature, can also be achieved through the use of nanotechnology [4]. Using the field effect transistor (FET) structure, highly sensitive sensors [5–7] or noise enhanced nonlinear devices [8,9] are possible. Of course, CNT-FET sensors have high sensitivity and nano-sized CNT-FETs are also promising as nano-devices; however, noise enhancement in relation to device performance seems to be an additional optimization of such high-performance devices to help application operation under conditions of noise, where nano carbon materials such as CNTs produce a large noise due to their nano-sized structures [10–12].

Such noise enhancements are commonly known in nonlinear systems. One of the constructive effects of noise is stochastic resonance (SR) [13,14]. At first, SR was proposed for ice-age periodicity [15]. Small changes in solar energy irradiated on the earth can cause ice-age transitions with the help of the environmental noise of the earth. Enhancements of the effect of small signals on nonlinear systems were then investigated, and many biological applications have been proposed such as the small signal detection in crayfish [16], information gain in ion channels [17], and signal processing in the human brain [18].

Artificial devices to demonstrate the effects of SR have also been fabricated using CNTs [19] and nanowires [20], where nonlinear properties of CNT-FETs or nanowires are used. The semiconductor neuron systems have also been fabricated [21] using nonlinearity. We also developed a noise enhancement biosensor and have successfully detected weak-signals in solution [22–24]. Therefore, noise enhanced biosensors seem to be suitable for the label-free detection of molecules. On the other hand, noise is also expected to be a large problem in nanoscale logic devices. A new working condition for complementary metal oxide semi-conductor (CMOS) devices is proposed on the basis of SR phenomena [25]. In this context, CNTs seems to be one of the model systems for such nanoscale

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Table 1
CNT samples list.

	Co thickness	Diameter of CNT (nm)
Sample 1	5 nm (EB)	~1.5
Sample 2	4 nm (APG)	~1.0
Sample 3	0.4 nm (APG)	~0.8
Sample 4	4 nm (APG)	~1.1

devices. As the high noise intensity of CNTs can simulate controllable noise in nanoscale devices, the whole nonlinear system with noise could then be combined on a single chip.

The control of noise in FETs is therefore important for actual device operations. We have also reported SR phenomena using the noise controlled by gate voltage [26]. For the further control of SR devices, the detailed study of noise seems to be required. Several origins of noise have been proposed, and defects and/or surface adsorption of molecules seem to be dominant for the 1/*f* type noise in CNTs [27]. In this paper, we analyzed the noise properties in CNTs using noise spectroscopy with different fabrication parameters or ambient environments.

2. Experiments

Co catalyst for CNTs was fabricated using an electron beam (EB) deposition or an arc plasma gun (APG) process. In the EB process, thin film was deposited and changed to nano particles during the CVD process for CNT growth. In the APG process, nano particles were deposited by the acceleration of the source materials on the substrate, where arc discharge generates the plasma of cathode materials. Therefore, the size of the catalyst is larger in the EB process than the APG process. CNT was grown by an alcohol CVD at 820 °C using these Co catalysts. The diameter of the CNT is larger with the catalyst of the EB process. The nano particle sizes were estimated using transmission electron microscopy, and the diameter of the CNT was estimated using atomic force microscopy. Using photolithography, a back-gate type FET was fabricated and Ti (1 nm)/Pd (25 nm) electrodes were deposited by EB evaporation. The catalysis deposition and thickness are summarized in Table 1, where the thickness for the nano particles is expressed as the equivalent thickness of a thin film. In this experiment, we selected the single channel CNT-FET as shown in Fig. 1(a).

FET properties were measured using a semiconductor device analyzer (B1500; Agilent Technologies). Time dependence of I_{DS} (drain-source current) was used as basic data for the noise analysis (Fig. 1(b)), where V_{DS} of 0.1 V and 0.2 V were used and the typical conductance at $V_g = -5$ V was 10^{-7} S. The detailed method for the noise analysis will be summarized in the next section.

The environments for sample 4 were controlled in the nano-prober system. At first, I_{DS} was measured in the air, and that in the vacuum environments at 6×10^{-4} Pa was measured after the pumping at room temperature. The parts of the adsorbed molecules were removed in this treatment. After the nitrogen gas purge, I_{DS} in the air conditions was measured again to check reproducibility.

3. Noise spectroscopy

For the stochastic processes, we used noise spectroscopy. Each process can be expressed by the random variables *X* as indexes. The probability function *P*(*X*) gives the probability of the process and defines the distribution of the process such as a Poisson or Gauss distribution [28]. We therefore select the suitable random variable and are able to split the processes into those that are caused by the different processes.

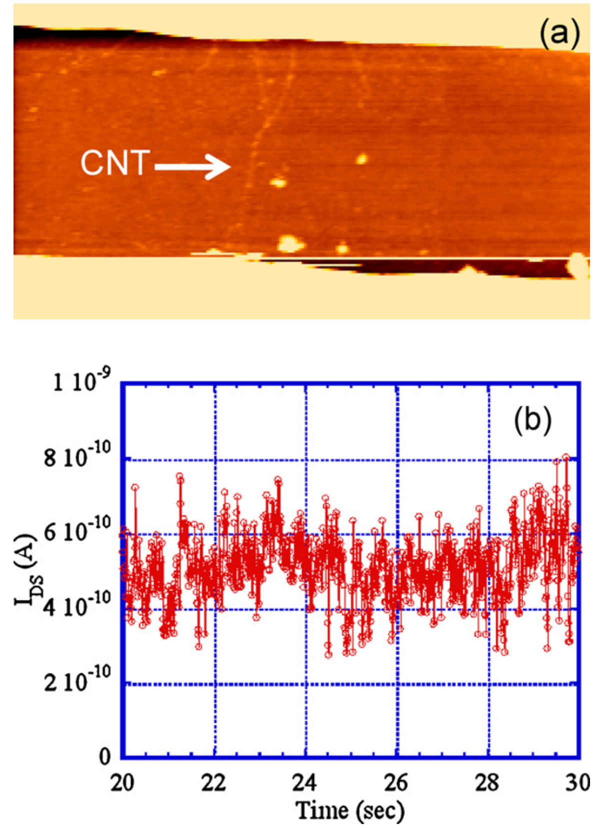

Fig. 1. Representative CNT channel in CNT-FET (a), and an example of the time dependence of I_{DS} (b).

The split of the processes can be estimated using a likelihood method. At first, the representative variables θ_t are defined, where they are expressed by an average value and standard deviation such as in the case of the Gauss distribution, and the likelihood function $L(\theta)$ is defined. To maximize $L(\theta)$, we can obtain a likelihood distribution for the stochastic processes.

In this paper, we select I_{DS} as the random variables and the Gauss distribution is used for the calculation. These Gauss distributions seem to have 1/*f* type noise, and then the total noise also becomes that of 1/*f* noise. Many groups have observed 1/*f* type noise in CNTs, including thin films and device structures. Dimensional analysis [10] and device size dependence [29] support 1/*f* type noise based on Hooge's phenomenological theory. The total carrier number defines the noise properties of CNTs, and the effects of diffusion seem to be small [11]. We have observed the gate voltage dependence of noise intensity [26], where the noise could be controlled by the carrier number. The surface charge can affect the carrier number fluctuation as carrier doping, and then both the scattering by the defects and surface adsorption can contribute to 1/*f* type fluctuation in CNTs. The diffusion of CNT crossing might generate diffusion noise [30], and defects interaction [12] might generate random telegraph noise. However, our measurements were done at room temperature and the power of 1/*f* is close to −1. Therefore, we used the 1/*f* type noise as the dominant noise features in our analysis.

In order to express the noise properties for each process, the power spectral density (PSD) of the noise was calculated through the Fourier transform with the Keiser Bessel window function. The PSD curve of the noise indicates the different features over and under the critical frequency around 5 Hz. In order to separate these two components, boxcar smoothing (moving average) of the noise was calculated as the component of the long-term fluctuation. The