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Single-Electron-Resolution Noise Analysis and Application Using High-Sensitivity Charge Sensor

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ABSTRACT

We introduce an analysis of thermal noise using a high-sensitivity charge sensor. Since the sensor is based on a Si field-effect transistor whose channel size is approximately 10 nm, the sensor exhibits sufficiently high sensitivity to detect single-electron motion even at room temperature. By connecting this sensor to a small capacitor comprising dynamic random access memory, thermal noise in the capacitor can be monitored in real time with single-electron resolution. Such real-time monitoring reveals that when the capacitor is sufficiently small that the charging energy for storing one electron in the capacitor is greater than the thermal energy, the thermal noise is suppressed and enhanced. This represents a deviation from the law of energy equipartition. In addition to this noise analysis, we present a successful demonstration of power generation using an analogy of Maxwell's demon that detects and manipulates single-electron motion, which should accelerate research in the field of thermodynamics. These experimental results show that the high-sensitivity charge sensor can function as a superior platform for microscopic analysis of noise, small electronic devices, and thermodynamics as well as a demonstration of theoretical expectation in basic research.

INTRODUCTION

Data processing circuits comprise a huge number of Si field-effect transistors (FETs) and their miniaturization has increased circuit performance. FETs have also been used as a signal amplifier or sensor for various kinds of applications such as memory circuits, image sensors, and chemical sensors. Si-FET sensors are advantageous due to their superior integration and miniaturization capabilities. In particular, the currently employed miniaturization technique established for data processing circuits achieves a nanometer-scale structure enabling a sufficiently high level of sensor sensitivity [1, 2] to detect an extremely small number of objects including proteins [3, 4], DNA [5], and ultimately a single charge [6]. Such improvement in the sensor sensitivity provides various merits to not only practical applications but also basic research. Some such merits for practical applications are high-resolution signal detection, fast sensing, and highly dense integration. Up-coming applications such as the quantum computers and quantum key distributions have also relied on highly sensitive sensors with single-electron and single-photon resolution. In the fields of basic research, high-sensitivity sensors have played important roles in revealing new phenomena and physics, and are vital to academics and applications in the future.

In this paper, we introduce analysis on electric noise using a Si-FET-based sensor. Since the sensor is sufficiently small to detect single electrons, noise analysis can be carried out with single-electron. Although single-electron detection reported elsewhere have been carried out at low temperature, miniaturization of the Si-FET-based sensor allows room-temperature operation. Additionally, a unique application taking advantage of single-electron detection, i.e., Maxwell's demon, is also shown.

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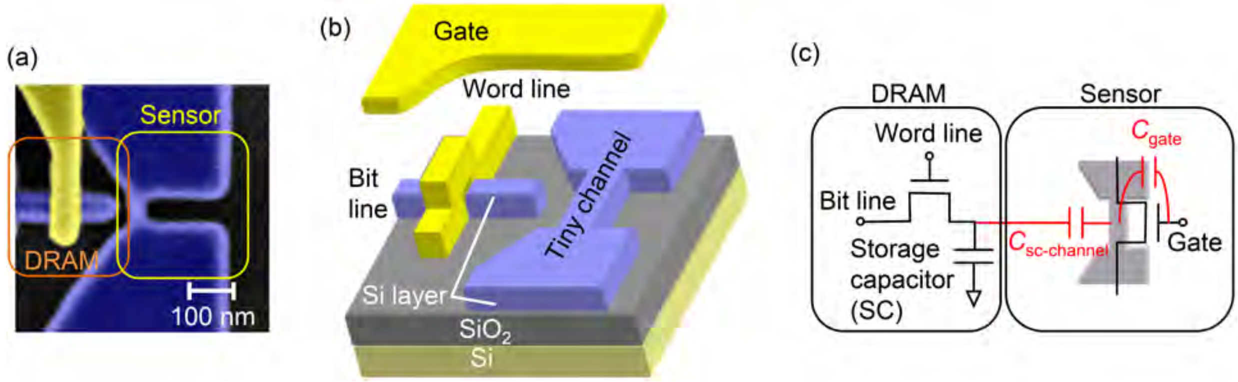

Fig. 1: Si-FET-based sensor integrated with DRAM. (a) SEM image. Entire area is covered with a gate electrode as shown in (b). (b) Birds-eye view. (c) Equivalent circuit.

FET-BASED SENSOR WITH SINGLE-ELECTRON RESOLUTION

Single-electron-resolution electric-noise analysis is carried out using a Si-FET-based sensor integrated with dynamic random access memory (DRAM) comprising one FET and one storage capacitor (SC) as shown in Fig. 1 [6]. By controlling the FET with word and bit lines, electrons are stored in or released from the SC and absence/existence of electrons in the SC is usually represented as one bit of information. Since the resistance of the FET is not infinite even in its off state, electrons are randomly shuttled between the SC and bit line due to thermal energy, which causes the thermal noise in the SC. In our analysis, this electron shuttling, i.e., thermal noise, is monitored with single-electron resolution using the sensor. Electrons in the SC modulate the current flowing through the sensor due to repulsive force between the electrons in the SC and those in the sensor channel. A key point for single-electron monitoring is the degree of current modulation, $dI_{\mathrm{modulation}}$. Following conventional noise analysis, we consider voltage noise V_{noise} instead of electron shuttling. In the most likely case that V_{noise} is sufficiently low to modulate the current flowing through the sensor linearly, $dI_{\mathrm{modulation}}$ can be given by

$$dI_{\mathrm{modulation}} = g_{\mathrm{m}}\,(C_{\mathrm{SC\text{-}channel}}/C_{\mathrm{gate}})\,dV_{\mathrm{noise}}, \qquad (1)$$

where g_{m} is the sensor transconductance defined as a gradient of current characteristics as a function of the gate voltage of the sensor, and $C_{\mathrm{SC\text{-}channel}}$ and C_{gate} are the capacitance between the SC and a tiny channel of the FET-based sensor and that between the gate and tiny channel, respectively, as shown in Fig. 1(c). To increase $dI_{\mathrm{modulation}}$, we must consider the following points. Transconductance g_{m} increases with the voltage between the source and drain electrodes of the sensor. Capacitances $C_{\mathrm{SC\text{-}channel}}$ and $C_{\mathrm{SC\text{-}channel}}/C_{\mathrm{gate}}$ are increased by locating the tiny channel very close to the SC and by reducing the size of the tiny channel, respectively. In our experience, the typical size of the tiny channel of the sensor is approximately 10 nm so that it can detect a single electron. Such a small size allows the sensor to behave as a single-electron transistor [7] at low temperature. Some reports show that single-electron transistors have good sensitivity characteristics due to their low background noise [2]. However, since single-electron transistors can operate at low voltages between the source and drain electrodes, g_{m} is low. Room-temperature operation is also extremely difficult. Therefore, we use the sensor based not on a single-electron transistor but on a conventional FET.

On the other hand, since V_{noise} is caused by fluctuation dQ of the charge in the capacitor, dV_{noise} can be given by

$$dV_{\mathrm{noise}} = dQ/C_{\mathrm{SC}}, \qquad (2)$$

where C_{SC} is the total capacitance of the SC. When the sensor detects a single electron, dQ is e, where e is the elementary charge of 1.6×10^{-19} C. From the viewpoint of experiments at room temperature, typical C_{SC} and V_{noise} values are 10 aF and 16 mV, respectively, which means that the SC size must be approximately 10 nm.

As mentioned above, the success of single-electron-resolution noise analysis is entirely dependent on how the small structure of approximately 10 nm is achieved. While various kinds of essentially small materials such as carbon nanotubes, graphene, and two-dimensional transition metal dichalcogenides have been studied, we take

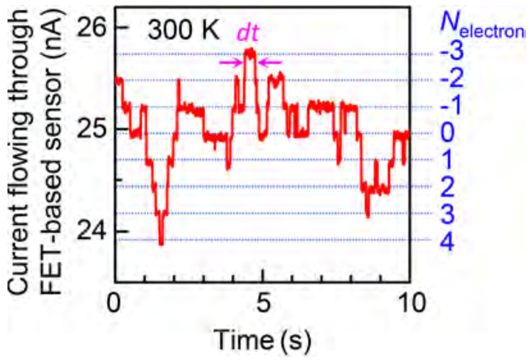

Fig. 2: Current flowing through FET-based sensor. Voltages applied to all electrodes are constant. The details are given in [8]. $N_{electron}$ is a deviation from the average of the number of electrons in the SC and dt is the interval during which electrons stay at the SC without electron injection/ejection.

advantage of well-established Si-transistor fabrication processes guaranteeing high reproducibility, further miniaturization, and high integrability. In order to achieve a small structure of approximately 10 nm, we used silicon-on-insulator wafers and shrank the electron-beam-patterned fine structure using an oxidation process [6].

SINGLE-ELECTRON-RESOLUTION ANALYSIS OF THERMAL NOISE

Figure 2 shows the change in the current flowing through an FET-based sensor when constant voltage is applied to all electrodes, which means that the DRAM is under an equilibrium condition. A change in the current shows a step-like pattern in which the step height is almost constant. This represents the situation when a single electron enters and leaves the SC. The current respectively decreases and increases by a constant quantity, which means that the sensor monitors electron shuttling between the SC and bit line in real time, and more importantly, at room temperature.

By using the change in current to represent electron shuttling as shown in Fig. 2, we can discuss the electron shuttling, i.e., thermal noise, statistically. As shown in Fig. 3(a), a histogram of deviation $N_{electron}$ from the average of the number of electrons in the SC exhibits a Gaussian function. Since e/C_{SC} multiplied by $N_{electron}$ corresponds to the voltage noise in the capacitor, the histogram also represents a distribution of voltage-noise amplitude. Additionally, Fig. 3(b) shows that a variance in the distribution of the voltage-noise amplitude, or mean-square voltage noise, follows the temperature dependence given by $k_B T/C_{SC}$, where k_B is Boltzmann's constant and T is temperature. This dependence is one of the well-known features of thermal noise. Another important signature of thermal noise is that interval dt of the current plateaus, in which electrons remain in the capacitor, are always random as shown in Fig. 2. Indeed, the frequency spectrum density of the voltage noise evaluated from temporal change in $N_{electron}$ multiplied by e/C_{SC} exhibits flat characteristics up to the cut-off frequency as shown in Fig. 3(c). These features mean that single-electron motion follows the well-known thermal noise model.

When C_{SC} is so low that charging energy $e^2/2C_{SC}$ for a single electron to be stored in the capacitor is greater than thermal energy $k_B T/2$, noise originating from the electron shuttling does not exhibit the well-known features of thermal noise [9]. As mentioned above, since

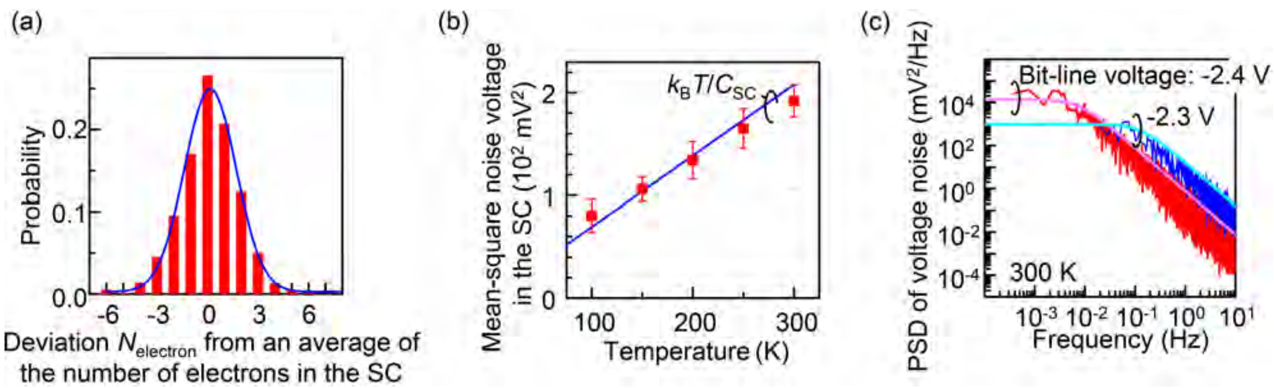

Fig. 3: (a) Histogram of deviation $N_{electron}$ from the average of the number of electrons in the SC. The solid line is the Gaussian function theoretically expected from thermal-noise model. (b) Dependence of Mean-square noise voltage in the SC, evaluated from a variance of the distribution of voltage-noise amplitude given by $N_{electron}\, e/C_{SC}$, on temperature. The solid line is given by $k_B T/C_{SC}$. (c) Power spectrum density of voltage noise evaluated from temporal change in $N_{electron}$ multiplied by e/C_{SC}. In order to channel resistance of FET, voltage applied to the bit line is changed. The solid line represents theoretical values. Details are given in [9].

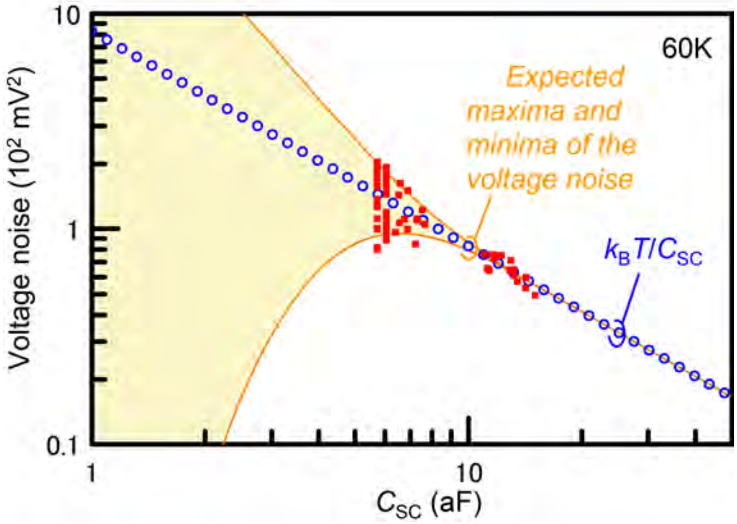

Fig. 4: C_{SC} dependence on voltage noise in the SC. Closed squares and open circles are experimental values and those given by k_BT/C_{SC}. The solid lines and shaded area represent expected voltage noise considering the charging energy and thermal energy. Details are given in [9].

thermal noise follows k_BT/C_{SC}, which is the so-called kT/C noise, reduction in C_{SC} increases the noise and thus disturbs the degree of device shrinkage especially in analog circuits. However, when C_{SC} becomes lower than e^2/k_BT, noise deviates from values given by k_BT/C_{SC} as shown in Fig. 4. The reason for this deviation is the Coulomb blockade [7], in which high charging energy in the capacitor suppresses unintentional electron shuttling driven by thermal energy. The degree of deviation depends on the difference between the electro-chemical potential of the capacitor and the Fermi energy of the bit line of the DRAM. In other words, while electron motion driven by thermal energy follows the law of energy equipartition at $e^2/2C_{SC} < k_BT/2$, an extremely small capacitor at $e^2/2C_{SC} < k_BT/2$ gives arise to a deviation from the law of energy equipartition. It should be noted that since this unique insight of thermal noise appears when the capacitance (or material dimension) reaches aF (or 10 nm) or less, any small material including carbon nanotubes, graphene, and molecules, also face the same phenomenon, i.e., deviation from the law of energy equipartition.

MAXWELL'S DEMON UTILIZING SINGLE-ELECTRON MOTION

Single-electron-resolution noise analysis highlights new insight into noise. On the other hand, real-time monitoring of single-electron motion allows us to demonstrate Maxwell's demon, which is an imaginary entity reducing the entropy of a system and generating free energy in the system. One famous example is the separation of hotter and colder gas particles in a box. The demon can identify randomly moving gas particles, their temperatures, and open/close a gate in the box to separate the hotter and colder particles, which creates a temperature difference and thus generates energy. This paradox, in which the second law of thermodynamics seems to be violated, had been clarified by the context of information thermodynamics [10].

The point of operation driven by Maxwell's demon is to identify the individual gas particles. In the same analogy, when gas particles are replaced with electrons by using a single-electron-resolution sensor, electric energy would be generated. For this operation, the sensor integrated with FETs functioning as a gate separating electrons was fabricated as shown in Fig. 5 [11]. The sensor monitors the number of electrons in the box between two FETs. When the left FET opens and an electron enters the box due to thermal energy, the left FET is closed and thus the electron is stored in the box. Then, when the right FET opens and an electron leaves the box, the right FET is closed. Consequently, electrons can flow from the left side to the right side although no energy is applied to the electron, i.e., current generation by Maxwell's demon. Even when the potential of the right side is higher than that of the left side, electrons can climb the potential because of thermal energy and thus gain energy. Repeating this operation generates electric power.

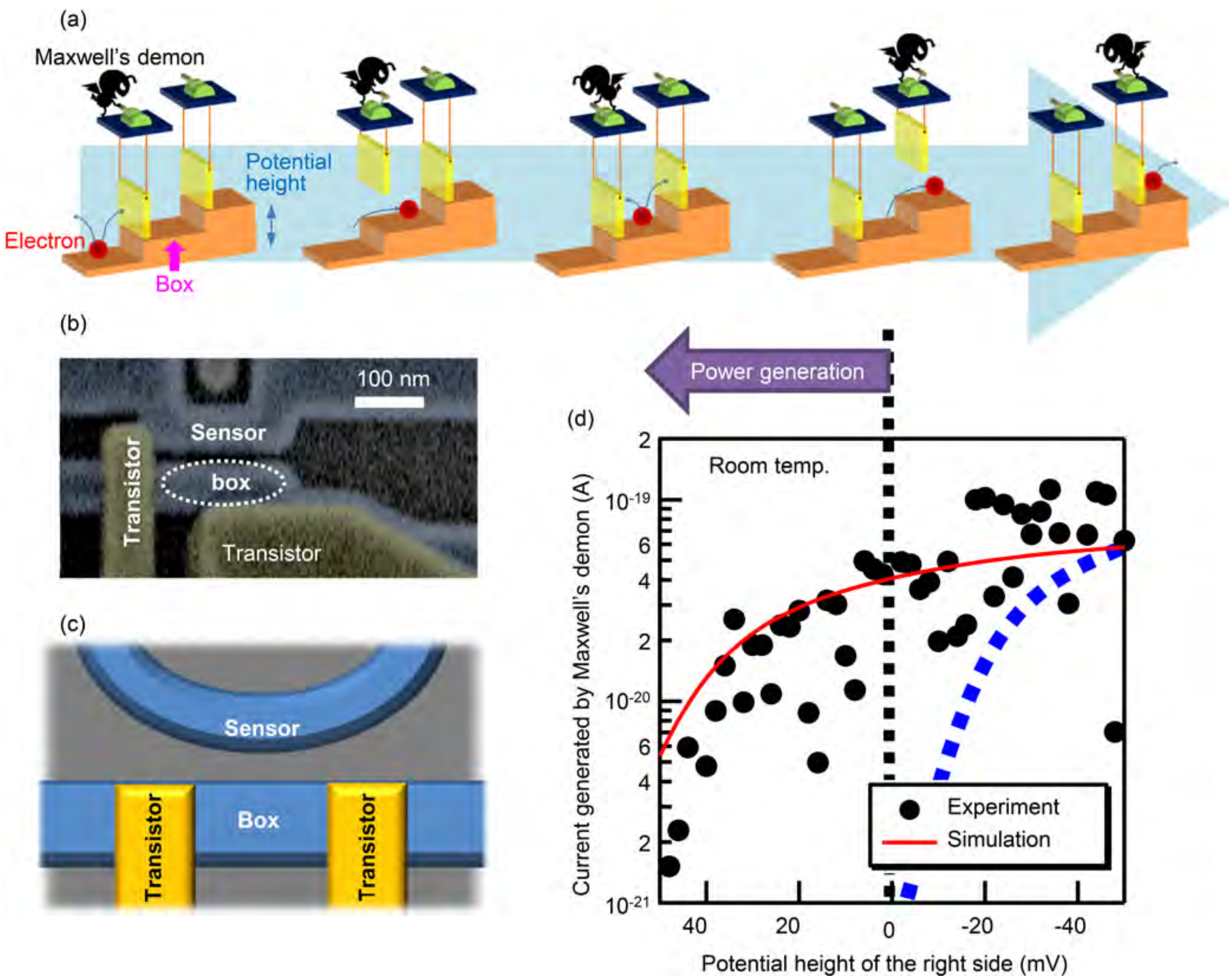

Fig. 5: (a) Schematics of a demonstration of Maxwell's demon. Maxwell's demon can monitor single-electron motion and open/close two gates according to electron's position. (b) Fabricated devices and (c) its schematics. Two transistors function as gates. (d) Change in current generated by Maxwell's demon when potential height of the right side to which electrons go is changed (see 5(a)). The solid and dotted lines represent simulated values.

Experimental demonstration of Maxwell's demon had been very difficult because of the extreme difficulty in identifying a single particle such as gas particles and electrons whose motion is driven by thermal energy. However, recently, single-electron transistors that can detect and manipulate single electrons have provided successful demonstration of Maxwell's demon utilizing single electrons [12]. The FET-based sensor described herein that detects single-electron motion has also succeeded in demonstrating this but, more importantly, at room temperature. Therefore, we believe that study on information thermodynamics would be accelerated by ultra-high sensitivity sensors and provide a hint toward achieving ultra-low-power consumption electric devices because information thermodynamics relates to the Landauer limit, which relates to the power consumption limit of digital circuits.

CONCLUSION

Thermal noise was analyzed with single-electron resolution. Thanks to its statistical analysis, we have observed unique features in which thermal noise in a small capacitor is suppressed and enhanced. This thermal noise originates from random electron motion under an equilibrium condition. In addition to thermal noise, suppression of shot noise under non-equilibrium conditions has also been reported [13]. Therefore, we believe that analysis of electron transport with single-electron resolution would highlight new insights in future electric devices of small dimensions.

Additionally, we demonstrated Maxwell's demon by taking advantage of the sensor feature of detecting single-electron motion as well as FET manipulation of it. Since the sensor operates even at room temperature, it can be used as a platform for studying fields such as information thermodynamics and electronics. Using such single-electron detection and manipulation, electric circuits using single electrons has also been achieved [14-20]. Therefore, Si FETs miniaturized by their ever-advancing fabrication techniques promise to open new fields of basic research and applications.

References

[1] M. J. Madou and R. Cubicciotti: Proc. IEEE 91 (2003) 830.
[2] M. H. Devoret and R. J. Schoelkopf: Nature 406 (2000) 1039.
[3] Y. Chui, Q. Wei, H. park, and C. M. Lieber: Science 293 (2001) 1289.
[4] E. Stern, J. F. Klemic, D. A. Routenberg, P. N. Wyrembak, D. B. Turner-Evans, A. D. Hamilton, D. A. LaVan, T. M. Fahmy, and M. A. Reed: Nature 445 (2007) 519.
[5] J. Hahm and C. M. Lieber: Nano Lett. 4 (2004) 51.
[6] K. Nishiguchi, C. Koechlin, Y. Ono, A. Fujiwara, H. Inokawa, and H. Yamaguchi: Jpn. J. Appl. Phys. 47 (2008) 8305.
[7] K. K. Likharev: IBM J. Res. Dev. 32 (1988) 144.
[8] K. Nishiguchi, Y. Ono, and A. Fujiwara: Nanotechnology 25 (2004) 275201.
[9] P. A. Carles, K. Nishiguchi, and A. Fujiwara: Jpn. J. Appl. Phys. 54 (2015) 06FG03.
[10] T. Sagawa and M. Ueda: Phys. Rev. Lett. 102 (2009) 250602.
[11] K. Chida, S. Desai, K. Nishiguchi, and A. Fujiwara: Nat. Commun. 8 (2017) 15310.
[12] J. Koski, V. Maisi, T. Sagawa, and J. Pekola: Phys. Rev. Lett. 113 (2014) 030601.
[13] K. Nishiguchi, Y. Ono, and A. Fujiwara: Appl. Phys. Lett. 98 (2011) 193502.
[14] K. Nishiguchi, Y. Ono, A. Fujiwara, H. Yamaguchi, H. Inokawa, and Y. Takahashi: Appl. Phys. Lett. 90 (2007) 223108.
[15] K. Nishiguchi, H. Inokawa, Y. Ono, A. Fujiwara, and Y. Takahashi: Appl. Phys. Lett. 85 (2004) 1277.
[16] K. Nishiguchi, A. Fujiwara, Y. Ono, H. Inokawa, and Y. Takahashi: Appl. Phys. Lett. 88 (2006) 183101.
[17] K. Nishiguchi, A. Fujiwara, Y. Ono, H. Inokawa, and Y. Takahashi: Appl. Phys. Lett. 90 (2007) 223108.
[18] K. Nishiguchi, Y. Ono, A. Fujiwara, H. Inokawa, and Y. Takahashi: Appl. Phys. Lett. 92 (2008) 062105.
[19] K. Nishiguchi and A. Fujiwara: Nanotechnology 20 (2009) 175201.
[20] K. Nishiguchi and A. Fujiwara: Jpn. J. Appl. Phys. 50 (2011) 06GF04.

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