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Control of Activation Energy for Electron Transport in Two-Dimensional Array of Si Nanodisks

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1. Introduction

The development of complementary metal-oxide-semiconductor large-scale integration (CMOS LSI) has led to faster and faster computer processing. However, some abilities, such as image recognition, are still not as advanced as those of the human brain, which has flexible processing functions such as association, perception, and reorganization. Therefore, a brain-like processing device needs to be applied to conventional digital processing.

In the brain, neurons are very important. A typical neuron has three parts: dendrites, a soma, and an axon. A spiking neuron model[1] can be used to explain the actions of a neuron when the dendrites receive spike input ($i_{in}(t)$ in Fig. 1). These inputs will generate a post-synaptic potential (PSP or P(t)), which is integrated as internal potential (I(t)) at the soma. Once the internal potential exceeds a threshold, the neuron emits a spike pulse ($i_{out}(t)$). The most important feature in this neuron model is the transformation from spike input to the decayed analog potential. The control of decayed time (time taken for PSP to change from the peak potential to resting potential) and P(t) height is also essential for integrating PSPs as internal potential.

To fabricate spiking neuron devices, some researchers have used single-electron devices with a two-dimensional multi-quantum-dot (2D multi-QD) structure that consists of QDs and tunnel junctions[2]. Both QD size and inter spacing between QDs affect the electron transport phenomenon in a 2D multi-QD structure; the former defines quantum confinement, and the latter determines the tunneling effect. However, although many processes have been proposed to form the 2D multi-QD structure[3,4] it is still a big challenge to control them independently and uniformly.

To overcome the problem in the fabrication process mentioned above, we have developed silicon nanodisk (ND) structures[5] using a bio-nano process comprised of ferritin bio-supramolecules and neutral beam (NB) etching[6]. We have also demonstrated a device with a 2D ND array based on the concept of 2D multi-QD devices. The ND structure has two geometric parameters, thickness and diameter, and they can be controlled independently. The ND structure shows a quantum effect with staircase characteristics, even at room temperature, and the staircase width is strongly dependent on its thickness, while it is independent of its diameter[7]. It has also been clarified that the 2D ND array has a quantum effect resulting from tunneling and quantum confinement effects.[8]

We investigated the current characteristics in a 2D ND array related to the actions of a neuron. We also explored the electron transport mechanism and control of its activation energy through a 2D ND array for the transformation from spike input to decayed analog potential.

2. Experiment

Fabrication of the 2D ND array was based on a bio-template process[6,10], which started with (i) the formation of a 100-nm-thick thermal oxide; (ii) a several-nm-thick poly-Si film was prepared (the ND thickness was determined by changing poly-Si thickness); (iii) a 3-nm thick SiO_2 film was grown on the poly-Si film using our developed neutral beam oxidation (NBO) process[10] (hereafter, the film is called NBO SiO_2); (iv) a 2-dimensional iron-oxide core (ϕ7 nm) array was prepared on the NBO SiO_2 surface as an etching mask; (v) an etching process was carried out using a combination of NF_3 gas/ hydrogen radical (NF_3 treatment) and NB etching. Both NF_3 treatment and NB etching are dry processes for selectively removing NBO SiO_2 and poly-Si, respectively (details of the etching process are described elsewhere[8]); (vi) after the etching processes, iron cores were removed with hydrochloric acid. The ND thicknesses were 2, 4, and 6 nm, and the inter spacing between NDs was approximately 2 nm. A device was fabricated by adding two chromium electrodes at both sides of the 2D ND array. Figure 2 shows a schematic of the device.

We measured the current response of the 2D ND array by applying pulsed voltage signals. Additionally, the current-voltage (I-V) characteristics were measured in a wide temperature range to investigate the temperature dependence of electron transport and its activation energy.

3. Results and discussion

Figure 3 shows a response signal by applying a pulse input signal to the device with the 2D ND array with a thickness of 2 nm. A decay curve was clearly observed, which indicates that the input pulse signal can be converted into an analog signal. It may be due to random electron hopping resulting from the quantum confinement of each Si ND, tunneling effect, electric field, and thermal noise in the 2D ND array (Fig. 3). While the thermal noise originates from the measuring environment, quantum confinement and tunneling effect can be controlled by the structure, in which these effects are observed, as activation energy regarding electron transport. To determine the activation energy, we investigated the temperature dependence of I-V curves on electron transport in the 2D ND array. I-V characteristics were measured from 20 to 373 K, and the resistances of the 2D ND array were then calculated. An Arrhenius plot of the resistances for 2-nm-thick NDs is shown in Figure 4(a). We found that the resistances hardly change at a low temperature ($T < 60$ K). On the other hand, as the temperature increases ($T > 60$ K), the resistances apparently decrease. This result suggests that electron transport is thermally activated with an activation energy of 0.31 eV. These results show that electrons in the 2D ND array overcome an energy barrier of 0.31 eV using thermal noise assist, which may result in decayed current signals, as shown in Fig. 3. This result suggests that the control of activation energy is important for controlling the decayed time of electron transport. The activation energy can be controlled by changing the quantum confinement and tunneling effect.[11,12] In the 2D ND array, the thickness and inter spacing can be engineered indenpendently[13], which suggests that the quantum confinement and tunneling effects can be controlled by changing the ND thickness and inter spacing, respectively. In this experiment, we investigated the dependence of the activation energy on ND thicknesses from 2 to 6 nm (Fig. 4(b)). We found that the activation energy of the 2D ND array can be controlled by simply changing the ND thickness. From these results, we speculate that decay time of output signals for spiking neuron devices can be precisely controlled by changing the ND thickness in a 2D ND array, even at room temperature.

4. Conclusions

We measured output signals for pulse inputs to investigate the electrical characteristics in a 2D ND array. The transformation from a pulse input signal to a decayed analog output one was clearly observed, which is required for actual spike neuron devices, and it may result from the random electron hopping in the 2D ND array. The activation energy for electron transformation in the 2D ND array and the decay time of output signals were precisely controlled by changing the ND thickness, even at room temperature.

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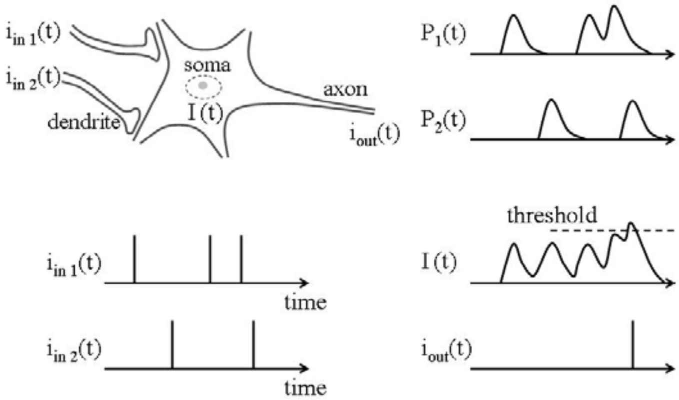

Figure 1. Schematic of spiking neuron model. The most important feature is the transformation from spike input to decayed analog potential

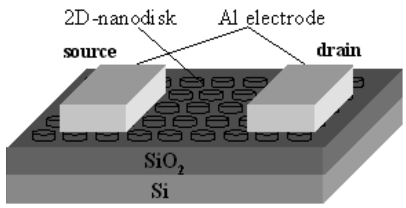

Figure 2. Schematic of device with 2D ND array

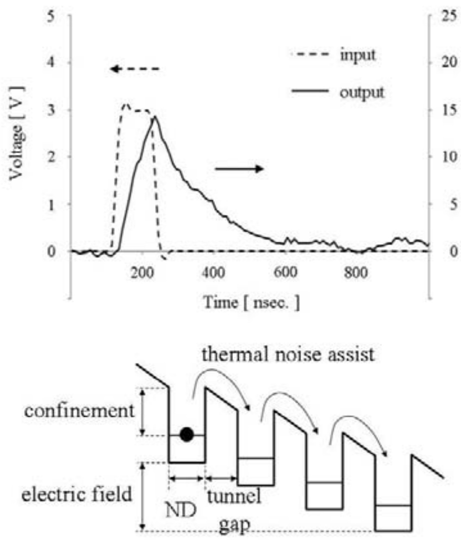

Figure 3. Response signal (I-t curve) for input pulse signal in 2D ND array. The signal may be due to random electron hopping resulting from quantum confinement, tunneling effect, electric field, and thermal noise assisting. The controlling of decay characteristic is essential for integrating PSPs as internal potential.

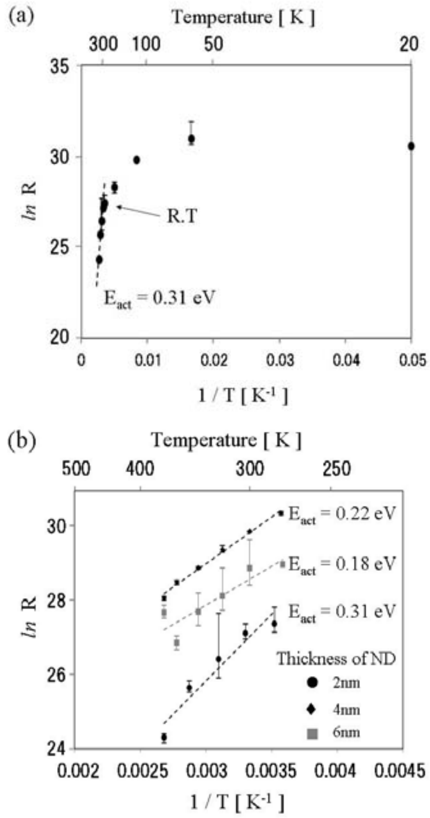

Figure 4. Arrhenius plots of resistances of 2D ND array with different ND thicknesses; (a) ND thickness: 2 nm from 20 to 400 K, (b) ND thickness: 2-6 nm from 270 to 400 K.