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Electrical and Magnetic Properties of Tunneling Device with FePt Magnetic Quantum Dots

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We have studied the electrical and magnetic transport properties of tunneling device with FePt magnetic quantum dots. The FePt nanoparticles with a diameter of 8～15 nm were embedded in a SiO_2 layer through thermal annealing process at temperature of 800^oC in N_2 gas ambient. The electrical properties of the tunneling device were characterized by current-voltage (I-V) measurements under the perpendicular magnetic fields at various temperatures. The nonlinear I-V curves appeared at 20 K, and then it was explained as a conductance blockade by the electron hopping model and tunneling effect through the quantum dots. It was measured also that the negative magneto-resistance ratio increased about 26.2% as increasing external magnetic field up to 9,000 G without regard for an applied electric voltage.

Keywords : FePt, Tunneling device, Quantum dot, Magnetoresistance

I. Introduction

Recently, the tunneling devices have been researched with various types such as thin film and quantum dots (QDs) tunnel junctions [1]. QDs are nano-sized zero-dimensional structures in which the motion of an electron is restricted in all directions. In such a region, quantum-mechanical effects dominantly appear. Currently, the study of QDs is important for quantum devices because QDs are expected to apply for quantum-bit, single-photon-source and single-electron memory devices [2]. On the other hand, the magnetic properties of QD are very interesting on spintronics application [3]. The ferromagnetic properties of FePt QDs have been reported [4]. Arrangement of different shaped nanoparticles into ordered patterns with specific packing by self-assembly or other techniques is an important step toward design of novel nanostructured materials and devices [5,6]. In particular, FePt nanoparticles have been widely studied because of their great application potential in advanced magnetic materials such as ultrahigh-density recording media and high-performance permanent magnets, based on their uniaxial magnetocrystalline anisotropy [7,8]. In this study, we have fabricated a tunneling device with FePt magnetic QDs and analyzed the electrical properties applying external magnetic fields using current-voltage (I-V) measurements. And then, the magnetotransport properties of the tunneling device with FePt magnetic QDs were analyzed by magnetoresistance measurements at 20 K.

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II. Experimental

The tunneling device with FePt magnetic QDs was fabricated on SiO_2/Si substrate. A SiO_2 oxide layer of 20 nm thickness was grown on p−type Si (100) wafer with resistivity of 1～30 Ω · cm by using plasma−enhanced chemical vapor deposition. The ultrathin FePt film with a thickness of 3 nm was deposited on the SiO_2/Si substrate by using direct current magnetron sputtering. For the formation of FePt nano−particles by thermal treatment a post annealing process was carried out at 500°C for 1 hour by using the rapid thermal annealing (RTA) under nitrogen (N_2) gas ambient. Then the next annealing process of the FePt QDs on SiO_2 surface was carried out at 800°C for 1 hour by using RTA under N_2 gas ambient. The tunneling SiO_2 layer with a thickness of 4 nm was deposited by using plasma−enhanced chemical vapor deposition. Finally, the Al nano−electrodes with 100 nm gap for a tunneling device with the FePt QDs between sources and drain were patterned by electron beam lithography technique. The I−V and magnetic properties of the tunneling and charging effects on FePt magnetic QDs were measured through the KEITHLEY 6487 electrometer with an external magnetic field at the temperature range of 20～300 K. The morphologies of the FePt QDs were observed using a transmission electron microscope (TEM).

III. Results and Discussion

The plane−view TEM image of the FePt QDs after RTA process at 800°C is shown in Fig. 1(a). Here, the size of the FePt QDs was approximately 8～15 nm. Several aluminum (Al) pads with nanometer dimensions are deposited by using standard e−beam lithography and lift−off procedures. Fig. 1(b) shows the optical microscope images of sharp−edged Al pads with a gap of 100 nm that are used as the source and the drain electrode. Fig. 1(c) is a schematic of a tunneling patterned sample. In tunneling device, the drain−to−source current flows via the FePt magnetic QDs that passes the SiO_2 tunnel oxide layer with

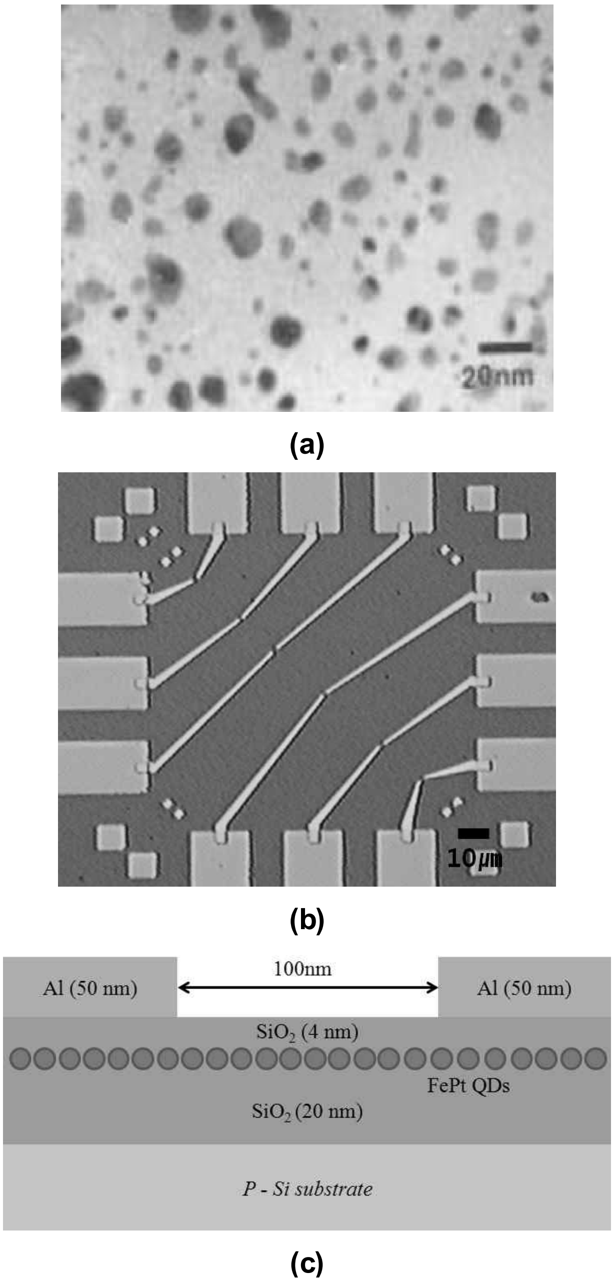


Figure 1. (a) Plane−view TEM image of the FePt QDs, (b) the optical microscope image and (c) the schematic diagram of the FePt magnetic QDs tunneling device.

tunneling effect.

The tunneling currents were measured in the device as shown in Fig. 2. It shows I−V characteristics of the tunneling device with FePt QDs at different temperatures. The source−and−drain series resistance gradually decreases as the ambient temperature decreases. The nonlinear I−V curves show to the single−electron transport phenomena at 20 K, while others are ohmic behavior. The resistance at 20 K was about order−of−magnitude smaller than the values measured at 230 K. This behavior was previously reported for different metal nanoparticle structures with the existence of tunnel barriers in the tunnel device, resulting in charging energy of single metal nanoparticles, which determines the electrical response of those films. An increasing temperature promotes thermal hopping of electrons which overcome the Coulomb blockade [9]. As a consequence, the resistance is rising with lower temperature in contrast to metallic films without tunnel barriers.

The nonlinearity in the I−V curves is only observable if the charging energy of particles is higher than the thermal energy. To analyze single− electron transport, we use an orthodox model [10]. Conductance varies rapidly at −0.64 V and 0.80 V bias voltages in Fig 3. According to the orthodox model, capacitance is calculated from the voltage gap. On assuming that electrons can move only one by one via QDs, the equation △V = e/Ceq expresses the relation between voltage gap and capacitance, and then the capacitance of the total system is calculated about 0.111 aF. However, the capacitance of a sphere with 10 nm diameter is obtained as 0.924 aF, theoretically. From the TEM image we can see about 8 particles in the 100 nm gap. So, the estimated capacitance with the number of particles is well in accordance with the experimental value. Therefore, we suggest that the electrons pass one by one through the FePt QDs.

Fig. 4(a) shows the negative magnetoresistance for various values of a perpendicular magnetic field from zero to 9,000 G with sweeping the bias voltage of ± 2 V. There are the tunneling effects of FePt magnetic QDs only at 20 K. The phenomena occurred from a combination of the total magnetization of FePt magnetic QDs and reduced thermal energy. These negative magnetoresistance, which appears to decrease the resistance with increasing magnetic field, observed in FePt magnetic QDs can be explained by spin dependent electron scattering and the effect of magnetic field on spin disorder resistivity. The external magnetic fields

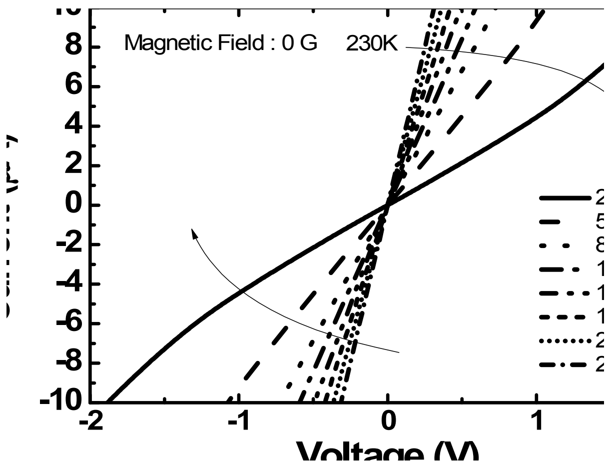


Figure 2. The I−V characteristics of tunneling device with FePt QDs on temperature range from 20 K to 230 K at zero magnetic field.

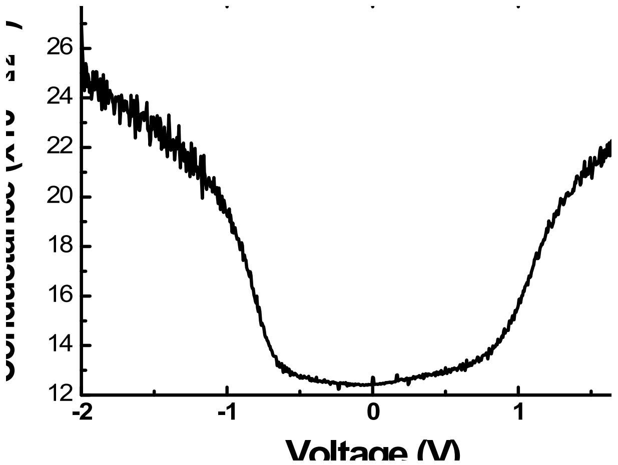
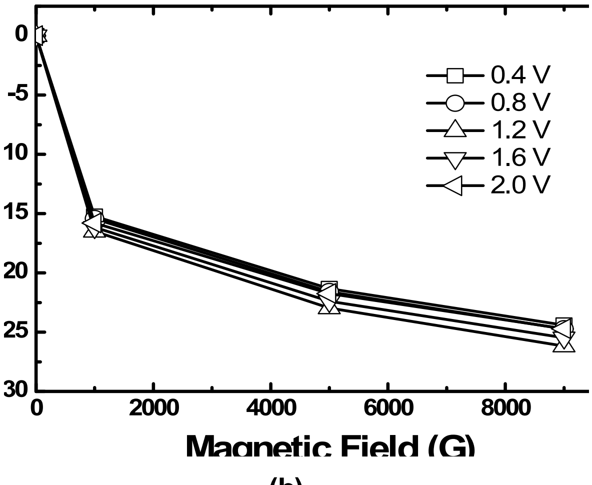


Figure 3. The G−V characteristics of tunneling device on the temperature of 20 K at zero magnetic field.

align the magnetic moments of the FePt magnetic QDs, thereby making the magnetization increase carrier conductivity [11]. Fig. 4(b) shows the magnetoresistance ratio, $R_{ratio}(MR) = \Delta R/R_0 = (R_0 - R_H)/R_0$, where R_0 and R_H are the resistance in zero magnetic field and in magnetic field H, respectively. There are increasing magnetoresistance ratios in 26.2% with applied voltage 2.0 V at a magnetic field of 9,000 G. The magnetoresistance ratio does not depend on the applied electrical potential, thereby the results only depended on the external magnetic field.

(a)



(b)

Figure 4. The I−V characteristics of tunneling device depending on (a) the magnetic field and (b) the magnetoresistance ratio characteristics with applied voltages at 20 K.

IV. Conclusions

The tunneling device with FePt magnetic QDs located between nano−gap electrodes was fabricated by simple curing process of metal films on SiO_2/Si substrates. The FePt nanoparticles with a diameter of 8∼15 nm were embedded in a SiO_2 layer through thermal annealing process at temperature of 800°C in N_2 gas ambient. From the temperature dependent I−V measurements, a nonlinear phenomenon appeared at 20 K was explained as a conductance blockade by the electron hopping model and tunneling effect through the quantum dots. The negative magnetoresistance ratio was increased with increasing magnetic field, and then it was measured about 26.2% at the magnetic fields of 9,000 G. These results showed that the tunneling device with FePt magnetic QDs has a possibility of the application to single−electron spin transistors.

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FePt 자기 양자점 터널링 소자의 전기적 특성과 자기적 특성 연구

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열처리 방식을 통하여 형성된 FePt 나노 입자를 사용하는 자기 양자점 소자를 제작하고, 전기적 및 자기적 특성을 연구하였다. FePt 자기 양자점 터널링 소자는 p 형 Si 기판 상부에 약 20 nm의 SiO2 터널 절연막을 형성하고 FePt 박막을 3 nm 두께로 증착한 후에 열처리 방식을 이용하여 8~15 nm 크기의 양자점을 갖는 구조이다. 터널링 소자의 전류-전압 특성을 자기장과 온도 변화에 따라 관찰하였고 특히, 저온에서 비선형적인 전류-전압 곡선을 확인하였으며 이러한 단전자 수송현상을 전자의 hopping 모델과 양자점의 터널링 현상을 이용하여 설명하였다. FePt 양자점 터널링 소자는 20 K에서 터널링 현상을 보였으며, 양단에 가해준 전압과 관계없이 외부 자기장이 증가할수록 음의 자기저항이 커지는 현상을 관찰하였고, 9,000 G에서 약 26.2 %의 자기저항 비를 확인하였다.

주제어 : FePt, 터널링, 양자점, 자기저항

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