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Relative Magneto-current of Magnetic Tunnel Transistor with Amorphous n-type Si Film

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A magneto-current (MC) was investigated for magnetic tunnel transistor (MTT) with amorphous n-type Si film. A relative MC (more than 49.6%) was observed at an emitter-base bias voltage (V_{EB}) of 0.65 V at room temperature. Above a V_{EB} of 0.70 V, however, a rapid decrease in MC was observed in the amorphous Si-based MTT. The collector current increasing and transfer ratio as emitter-base voltage were mainly due to the rapid creation electrons of conduction band states in the Si collector. This approach would make integration in various components and systems easier than a MTT grown on a semiconductor wafer.

Key words : magneto-current, magnetic tunnel transistor, amorphous n-type Si film, emitter-base bias voltage, collector current, transfer ratio

1. Introduction

A hot topic in the spin electronics research field is the performance of the magnetic random access memory (MRAM) and logic magnetic tunnel transistor (MTT), considering the same conditions of charge and spin degree of freedom [1-3]. The magnetic tunnel junction (MTJ) type MTT device developed by S. S. P. Parkin's research group features the pinned layer of MTJ as the emitter, the free CoFe layer as the base, and the n-type GaAs substrate as the collector using the energy difference of the injected hot electrons according to emitter-base voltage (V_{EB}). On other hand, the structure of spin valve type MTT device uses Cu or Au layers as the emitter and the spin valves as the base. Given two MTTs, the attenuation length (λ_{maj}) of hot electrons at the base is 60-90 Å to correspond to V_{EB} = 1.0~1.8 V. They reported that the transfer ratio (collector current: I_C/emitter current: I_E) go through the base maintained at about 10^{-4} [4, 5]. Likewise, up to a thick-base layer of 120 Å, a magneto-current (MC) depending on the external magnetic field has a maximum and a minimum value corresponding to the magnetization array of parallel and anti-parallel, changing from 65% to 1250% at 77 K [6, 7]. Based on these results, the development of an MTT device has emerged as an important issue. Nonetheless, MTT with Si or GaAs substrate posed several problems such as leakage current caused by a wide collector electrode, formation of silicide layer, and impurity at the interface. This paper introduced the fabrication of a new MTT structure and reported its characteristics using the collector of n-type Si amorphous thin films as the top layer.

2. Experimental

MTT multilayer films with a structure of [Ta(50 Å)/NiFe(120 Å)/FeMn(200 Å)/NiFe(40 Å)/CoFe(30 Å); emitter]/Al_2O_3(20 Å)/[CoFe(50 Å); base]/[Si(100 Å)/Al(100 Å); collector] were deposited via the ion beam deposition system with base pressure of 4×10^{-9} Torr. A 3-cm Kaufmann source was used as the ion gun and operated with argon gas at 1.4×10^{-4} Torr with beam voltage of V_b = 800 V and beam current of I_b = 6 mA for deposition [8]. A magnetic field (300 Oe) was applied during the deposition of MTT multilayer films in order to induce magnetic anisotropy. To limit interface damage, V_b was reduced to 500 V for Al barrier layer and Si layer collector. Layer thickness was monitored using a quartz balance. Al_2O_3 was formed through reactive oxidation for 10 min at 1 mTorr using electron cyclotron resonance (ECR) oxygen-ion in the other chamber.

As the base-emitter, the MTJ was patterned with conventional shadow metal masks having a junction area

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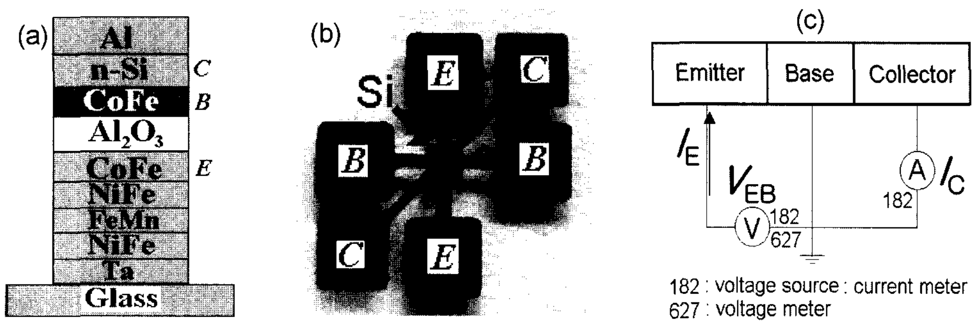

Fig. 1. (a) Multilayer structure and (b) photo image of the active area of a MTT with an amorphous n-type Si film. (c) The electric circuit indicating voltage source, current meter, and voltage meter in order to measure the emitter current (I_E), the collector current (I_C), the transfer ratio (I_C/I_E), and magneto-current (MC).

of 200 × 200 μm^2. As the collector, the 100 Å-thick amorphous n-type Si film was covered with 500 × 500 mm^2 over the base layer. Figs. 1(a) and 1(b) show the multilayer structure and real optical microscope picture of the MTT, respectively. From Fig. 1(b), the schematic of MTT designed four regions, region 1 represents the emitter, region 2 the Al_2O_3 tunneling barrier, region 3 the base, and the n-type Si films act as the collector. In order to measure emitter current (I_E), collector current (I_C), transfer ratio (I_C/I_E), and MC, we employed voltage source, pico-current meter, and nano-voltage meter as shown in Fig. 1(c). The transport properties of MTT were characterized by measuring the TMR and MC curves and *I(V)* response curves at room temperature.

3. Results and Discussion

The morphological, electronic, and optical properties of the amorphous n-type Si layers were characterized using atomic force microscopy (AFM), Hall resistance-temperature curve, and photon transmittance measurement [9], respectively. The amorphous Si semiconductor films had surface rms roughness of 1.1 Å, conductivity of 2.1 × 10^{-4} [Ωcm], carrier concentration of 2.0 × 10^{-20} cm^{-3}, and relatively high energy band gap of 2.27 eV, which is obtained by the fitting data from the optical band gap curve.

Fig. 2(a) illustrates the TMR curve for the Ta(50 Å)/NiFe(120 Å)/FeMn(200 Å)/NiFe(40 Å)/CoFe(30 Å)/Al_2O_3 (20 Å)/CoFe(50 Å) MTJ structure, which was obtained by measuring the voltage (V_{EB}) and current (I_{EB}) between the emitter and base electrode depending on the external magnetic field. At V_{EB} = 50 mV, the maximum value of TMR was 17.5%. Typical nonlinear *I(V)* characteristics included the indiscriminate difference in two *I*-*V* curves when the magnetization vectors among the pinned ferromagnetic/barrier/free ferromagnetic layers at the external magnetic fields of 15 Oe and 1000 Oe were anti-parallel and parallel, respectively. Fig. 2(b) shows the tunneling junction resistance curves depending on bias voltage (V_{EB}). The bias voltage dependence of TMR in the emitter-base MTJ can be drawn from Fig. 2(b), although it is also

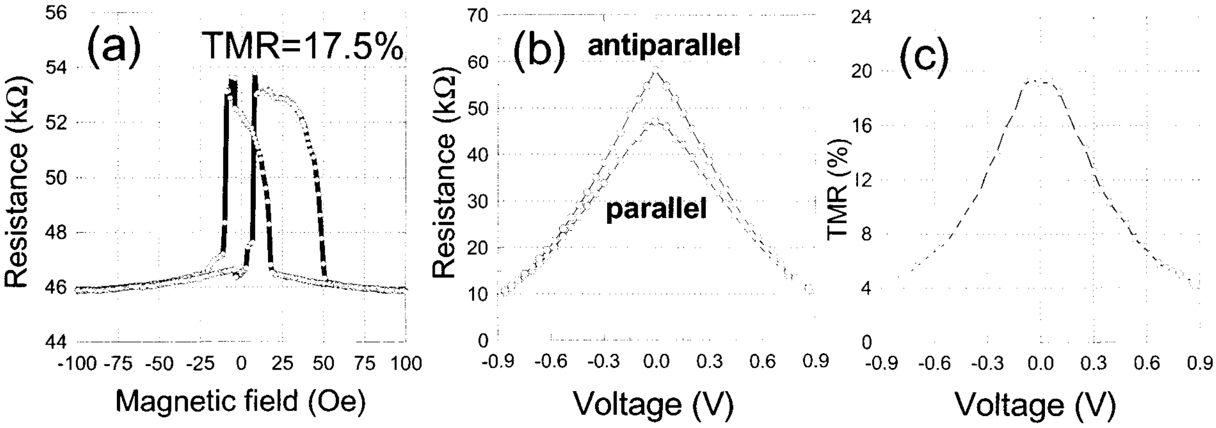

Fig. 2. (a) TMR curve, (b) bias voltage dependence of resistance, and (c) bias voltage dependence of TMR for the Ta(50 Å)/NiFe(120 Å)/FeMn(200 Å)/NiFe(40 Å)/CoFe(30 Å)/Al_2O_3(20 Å)/CoFe(50 Å) MTJ structure consisting of emitter and base in MTT.

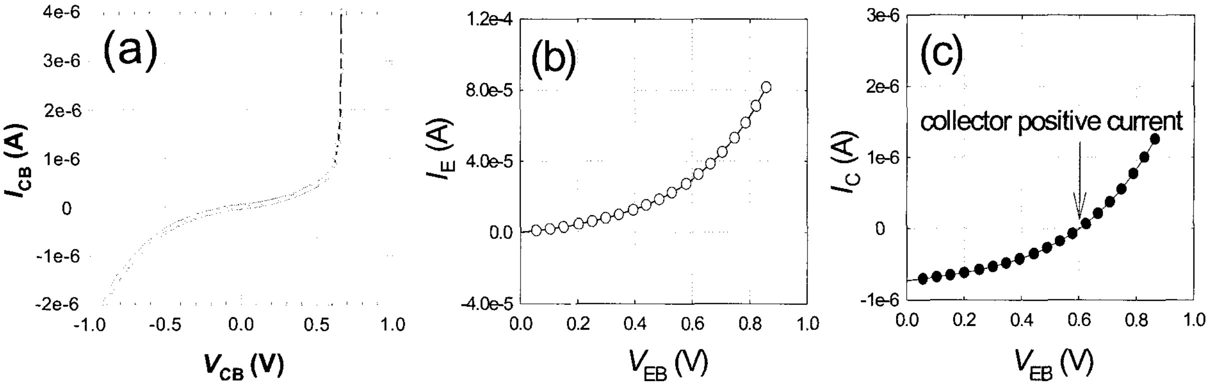

Fig. 3. (a) I-V curve of CoFe(50 Å)/Al_2O_3(t = 0)/n-Si(100 Å)/Al(100 Å) with a junction area of 200 × 200 μm^2. The emitter-base bias voltage (V_{EB}) dependence of (b) the emitter current (I_E) and (c) the collector current (I_C). The arrow indicates that the negative value of I_C changed to a positive value in the region of V_{EB} = 0.57~0.62 V.

present in Fig. 2(c). Bias voltage at half maximum TMR value was at 430 mV, which showed typical TMR properties for bias voltage [10].

Constant voltage was applied to the emitter and base electrodes of the MTJ, and base-collector current was measured. Fig. 3(a) presents a characteristic *I(V)* curve of B-C with junction area of 200 × 200 μm^2, which was fabricated through the shadow mask process. A nonlinear *I(V)* characteristic shows the rectifying property of diode, which is similar to Schottky diode [9] with forward knee voltage of about 0.6 V, although the silicides of CoSi or FeSi at the interface always exist at room temperature. Fig. 3(b) and Fig. 3(c) show the V_{EB} dependence of I_E and I_C. I_E changed from 1 μA to 80 μA as V_{EB} increased from 0.05 V to 0.87 V. Another point is that the collector current in Fig. 3(c) appears to be negative and exhibits a curious sign reversal. That is, I_C changed from -70 nA to -7.3 nA as V_{EB} rose from 0.05 V to 0.57 V. In particular, the negative value of I_C changed to a positive value in the region of V_{EB} = 0.57~0.62 V with emitter voltage dependence of transfer ratios (I_C/I_E) of 0.01~0.001. This implies that the electrons throughout the base layer pass over the collector layer. This phenomenon seems like that the collected electrons at the collector are hot electrons.

The attenuation length for the hot electron in MTJ was about 100 Å larger than the free layer thickness of CoFe(50 Å). The collector current curves depending on emitter-base voltage as a function of the applied magnetic field were shown in Fig. 4. There is the relative direction of the base magnetic moment due to the variation of the external magnetic field of 15 Oe at V_{EB} = 0.65 V. The maximum MC for the switching magnetic moment of base layer obtained from the change of collector current from 0.22 μA to 0.33 μA at room temperature. The calculated 49.6% MC is shown in the middle part of Fig. 4. The leakage current at interface CoFe/Si by the large junction area apparently decreased to zero at V_{EB} = 0.62 V. Likewise, the rapidly created MC was mainly due to an increase of electrons in conduction band states in the Si collector because energy band state is not change, but electrons in conduction band is changed due to the Fermi energy level. The MC at the interface between the magnetic CoFe layer and amorphous n-type Si semiconductor layer was enhanced at the neighboring region of Fermi energy level through the injected electrons from the emitter as the external magnetic field was swept. On other hand, the

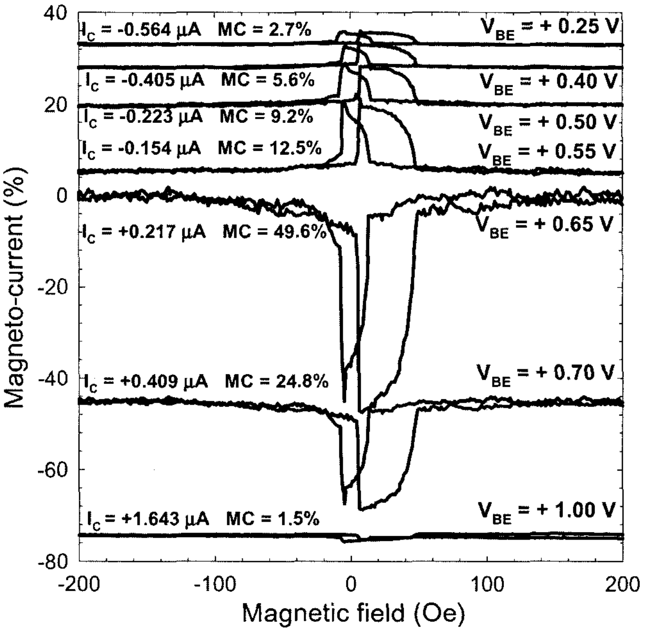

Fig. 4. Magneto-current curves depending on emitter-base voltage as a function of the applied magnetic field. The relative maximum MC of 49.6% obtained from the change of positive collector current from 217.0 nA to 324.7 nA at V_{EB} = 0.65 V.

MC rapidly decreased above $V_{EB} = 0.70$ V. This result can be explained by several factors, such as; the leakage current effect through pinholes inside the junction, the inhomogeneous geometry effect given a large junction size, and the electron with ballastically inelastic scattering across CoFe/Si interface.

On the other hand, the Si layer is only 100 Å thick and has very low resistivity of 2×10^{-4} Ωcm. Under such conditions it is unreasonable to expect a good energy barrier that act as a hot-electron high-pass filter, as is required for a proper MTT. In addition, amorphous Si contains a large density of defect induced band gap states. It is unclear what the nature of the base-collector barrier is, if any exist at all. Firstly, the electrical characterization of the base-Si junction is insufficient. It certainly does not behave as a diode, and a non-linear I-V curve does not suggest an ideal Schottky barrier. The low resistivity of amorphous n-type Si collector is should be compared to typical base-collector diodes in MTT and spin valve transistor (SVT), which have resistance of 100 MΩ or larger [4-7].

Therefore, any possibility of the interpretation of the data without hot electron transmission is exist. All data in Fig. 3(c) and Fig. 4 can be explained by voltage drops in the base leads. We note that the actual MTT junction region is connected to the base bond pad by a thin metal strip of about 200 μm width, which has a resistance of 5 Ω. When the bond pad is at ground potential, the base in the MTT junction area is not at ground potential when there is a non-zero emitter current. The emitter current through the 5 Ω base lead causes a potential difference between base and collector in the MTT area, and this in turn causes a collector current, even without any hot electron transmission. For emitter currents up to 80 μA, the voltage drop is only 0.4 mV. However, with the low resistance (~500 Ω) base-collector junction in the MTT, this easily produces collector currents on the order of μA, as observed in Fig. 3(c). The system thus acts a simple resistor network, which explains why one obtained transfer ratios of 0.01, which are unreasonably much larger then any MTT or SVT has shown so far. The above mechanism also causes the magnetic field dependence of the collector current in Fig. 4. When the magnetic field is changed, the emitter current changes, this causes the voltage drop across the base lead to change, which produces the change of collector current. The reported MC of 49.6% in Fig. 4 can be interpreted by a consequence of the sign reversal. In the vicinity of the zero crossing, the relative MC (relative collector current change) will grow as the denominator in the relative MC expression approaches zero current. At the zero crossing, the MC will even become infinite.

4. Conclusion

Amorphous Si film-based MTTs were characterized. Through the fitting and experimental curves for the n-type a-Si films analyzed via optical transmittance, an energy band gap (E_g) of 2.27 eV. An MTT device using the shadow metal mask had a patterned junction area of 200 x 200 μm^2. Given an MTT structure of Ta(50 Å)/NiFe (120 Å)/FeMn(200 Å)/NiFe(40 Å)/CoFe(30 Å)/Al_2O_3(20 Å)/CoFe(50 Å)/Si(100 Å), emitter-base tunneling magnetoresistance was at 17.5%. The relative maximum collector current change of MTT as a function of the applied magnetic field was about 49.6% at room temperature. The abrupt creation of collector current and transfer ratio (I_C/I_E) at any emitter-base voltage (V_{EB}) was mainly due to the increase in the number of conduction band states in the Si collector. Above a V_{EB} of 0.65 V, however, a rapid decrease in MC was observed. This approach would make integration in various components and systems easier than a MTT grown on a semiconductor wafer.

Acknowledgement

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