Characterization and analysis of a novel hybrid magnetoelectronic device for magnetic field sensing

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Structures in which magnetic and electronic materials are combined offer a variety of possibilities for realization of devices with improvement functionality or performance compared to conventional devices. We have designed, characterized, and analyzed a novel hybrid magnetoelectronic device: a monolithic field-effect-transistor-amplified magnetic field sensor in which a granular tunnel magnetoresistive (TMR) thin film, consisting of Co nanoparticles embedded in an insulating SiO_2 matrix, is incorporated into the gate of a *p*-channel Si metal-oxide-semiconductor field-effect transistor. In this structure, current flow through the TMR film leads to a buildup of electronic charge within the gate due to the Coulomb charging energy of the Co nanoparticles, and consequently to a transistor threshold voltage shift that varies with applied external magnetic field. In a prototype demonstration device, the relative current change induced by application of a 6 kOe external magnetic field at room temperature was amplified from 5% for the current through the TMR film to 21% for the transistor subthreshold current. The absolute current response in the saturation regime increased by a factor of about 500 compared to that of the TMR film alone. A detailed analysis of the device operation and of methods for optimization of performance are presented. It is anticipated that substantially better performance should be achievable with relatively straightforward improvements in device design and processing. This device concept is shown to compare particularly favorably with Hall bar sensors and thus may be very beneficial in sensor applications for medium field ranges up to about 1 T. © *2000 American Vacuum Society.* [S0734-2101(00)04504-8]

I. INTRODUCTION

Future magnetic data storage systems will require magnetic field sensors with improved sensitivity at room temperature. Currently, sensors utilizing the giant-magnetoresistance (GMR) effect in spin-valve structures are used in read heads of hard disks. In addition, GMR films have been investigated for more general applications such as angle, rotation speed, and position sensors.[1]

Magnetic tunnel junctions (MTJ), in which two magnetic layers are separated by an insulating nonmagnetic barrier instead of the magnetic metal layer as in spin-valve structures, have also shown considerable promise as candidates for use in magnetic field sensors for data storage applications.[2] MTJs offer a variety of attractive properties compared to GMR structures. The insulating interlayer eliminates exchange coupling between the magnetic layers, giving MTJs a higher field sensitivity. In addition, the absence of shunting currents yields improvements in the magnetoresistance (MR). However, a critical part of these MTJs is the quality of the insulating barrier. The fabrication of smooth, pinhole-free barriers with controllable dielectric properties and reproducible results remain major challenges.[3,4] As an alternate system, discontinuous magnetic metal/insulator multilayers have been proposed to alleviate the above difficulties.[5] These structures consist of ferromagnetic particles embedded in an insulating matrix. They are easy to fabricate, are robust due to the protection of the magnetic metal particles by the insulator, and are more reliable since the system consist of thousands of tunnel junctions and thus, defects are confined to individual junctions. However, the MR ratio of these materials is quite low and the saturation field is large.[6]

Recent studies of charge transport phenomena in similar types of magnetoresistive thin films have suggested an additional, new approach for achieving increased magnetic field sensitivity by incorporation of the MR film within an electronic device structure. Specifically, the observation of charge storage with retention times of up to several minutes in discontinuous magnetic metal/insulator multilayer structures[7] led to the design and demonstration of a novel monolithic field-effect-transistor-amplified magnetic field sensor.[8] In this device, a granular tunnel-magnetoresistive (TMR) thin film was incorporated within the gate structure of a *p*-channel metal-oxide-semiconductor field-effect transistor (MOSFET). The design allows for relatively simple fabrication and monolithic integration with other semiconductor components for increased sensitivity and functionality. In this article, we present detailed characterization and analysis of operation of this device.

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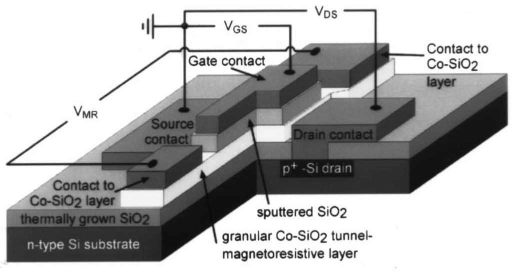

FIG. 1. Schematic diagram of the monolithic transistor-amplified magnetic field sensor device in which a magnetoresistive layer is incorporated within the gate structure of a Si MOSFET.

II. DESIGN AND FABRICATION

The sensor design is based on the incorporation of a granular tunnel-magnetoresistive film, consisting of 20 nm thin $Co_{0.41}(SiO_2)_{0.59}$, within the gate structure of a MOSFET, as shown in Fig. 1. The detailed device fabrication process is given in Ref. 8. Previous reports have shown that the Co/SiO_2 film deposited under these conditions consists of Co clusters with an average diameter of about 4 nm embedded in a SiO_2 matrix.[5,6] Studies of local charge injection and transport in similar Co/SiO_2 magnetic multilayer structures have demonstrated that such films are characterized by non-negligible charge storage and transport times that are highly sensitive to the detailed film structure.[7]

The observation of charge storage associated with current transport combined with substantial magnetoresistance in these materials implies the possibility that the threshold voltage in the MOSFET will vary significantly with an externally applied magnetic field. If a fixed voltage V_{MR} is applied across the Al contacts to the magnetoresistive thin film, a current I_{MR} will flow and charge per unit area Q_{MR} will be stored in the Co clusters. An analysis of Gauss's law for a cross section through the granular magnetoresistive layer (Al contact–SiO_2 barrier–Co clusters–SiO_2 barrier–Al contact) shows that for ohmic Al contacts, the charge per unit area Q_{MR} at equilibrium is given by

$$Q_{MR}=\frac{\varepsilon_{SiO_2}\varepsilon_0}{d}(R_1-R_2)I_{MR}, \tag{1}$$

where ε_{SiO_2} is the relative dielectric constant of SiO_2, ε_0 is the vacuum permittivity, R_1 and R_2 are the resistances of the first and second Al contact to the $Co_{0.41}(SiO_2)_{0.59}$ layer, and d is the thickness of the oxide barrier between the Al contacts and the Co clusters. Due to the Coulomb charging energy E_0 of the Co clusters, electrons tunneling from the Al contact into the Co clusters within the granular film must provide the additional energy E_0 and electrons tunneling out of the Co layer into the second Al contact release the energy E_0. As a result, the effective barrier heights ϕ_1 and ϕ_2 for the first and the second Al contact, respectively, are given by $\phi_{1,2}=(\phi_{Al}+\phi_{Co}-2\chi_{SiO_2}\pm E_0/q)/2$, where ϕ_{Al} is the Al work function, ϕ_{Co} is the Co work function, χ_{SiO_2} the SiO_2 electron affinity and q the electron charge. For a small voltage drop V across the SiO_2 barrier between an Al contact and the Co clusters, the current I is proportional to V according to $I=I_0V\sqrt{\phi}\exp(-A\sqrt{\phi})$, where A and I_0 are constants.[9] Thus, for ohmic behavior of the contacts and for small Coulomb-blockade energies $E_0\ll\phi_{1,2}$, the difference in contact resistances, R_1-R_2, will be given approximately by:

$$R_1-R_2\approx\frac{Ae^{A\sqrt{(\phi_{Al}+\phi_{Co}-2\chi_{SiO_2})/2}}}{I_0(\phi_{Al}+\phi_{Co}-2\chi_{SiO_2})}E_0. \tag{2}$$

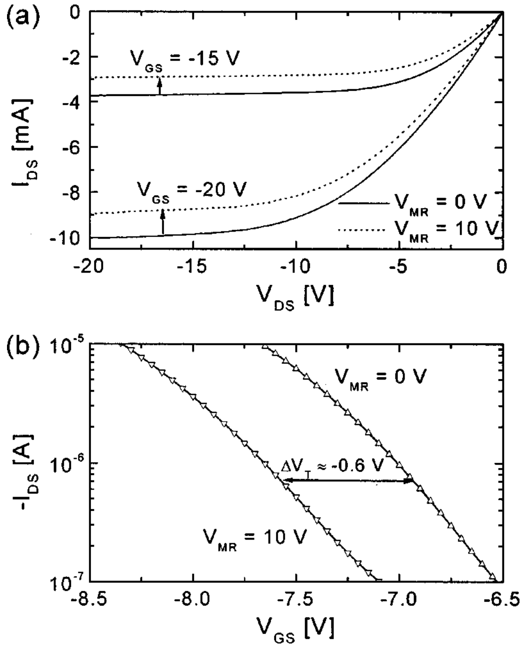

FIG. 2. (a) Transistor current–voltage characteristics for $V_{MR}=0$ V and for $V_{MR}=10$ V; (b) subthreshold current–voltage characteristics for $V_{MR}=0$ V and $V_{MR}=10$ V, showing a clear shift in threshold voltage of about 0.6 V, arising from the presence of stored charge within the gate.

Due to the magnetoresistance of the granular film, the current I_{MR} and thus the stored charge Q_{MR} in the Co clusters will vary in the presence of an externally applied magnetic field H. In a manner analogous to that observed in floating gate devices, the charge Q_{MR} stored in the granular film will cause a shift in the transistor threshold voltage, $\Delta V_T=-Q_{MR}/C_{ox}$, where C_{ox} is the capacitance of the upper oxide layer within the gate.[10] Thus, the threshold voltage shift will depend on the magnetic field according to the relation

$$\Delta V_T(H)\propto\frac{E_0\Delta I_{MR}(H)}{C_{ox}}. \tag{3}$$

This leads to a modulation of the transistor drain-source current with magnetic field, and consequently to a large amplification in the transistor current of the magnetoresistive response I_{MR} to an externally applied magnetic field.

III. RESULTS AND DISCUSSION

A. Zero-magnetic field characteristics

Figure 2(a) shows the transistor drain-source current I_{DS} as a function of the drain-source voltage V_{DS} and the gate-

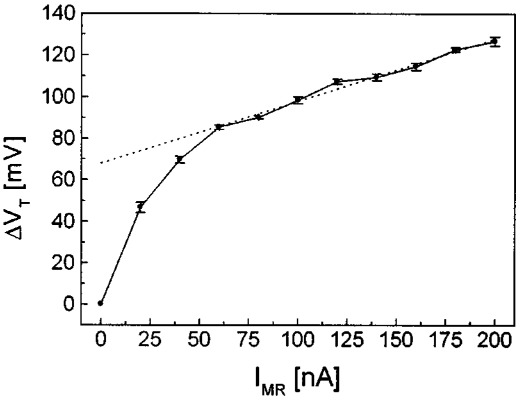

FIG. 3. Shift in transistor threshold voltage ΔV_T as a function of current $I_{\rm MR}$ through the magnetoresistive layer. The sharp increase in ΔV_T for small $I_{\rm MR}$ is a result of non-ohmic behavior of the Al contacts to the magnetoresistive layer. The dotted line shows the theoretically expected linear dependence of ΔV_T on $I_{\rm MR}$, which is observed at higher current levels.

source voltage $V_{\rm GS}$. Figure 2(b) shows the subthreshold current–voltage characteristics. In both figures, the solid line represents the results for $V_{\rm MR}=0$ V and the dotted line those for $V_{\rm MR}=10$ V. In the subthreshold regime, the drain-source current $I_{\rm DS}$ decreases upon application of a nonzero voltage $V_{\rm MR}$ across the magnetoresistive layer due to a positive threshold voltage shift of ~ 0.6 V along the voltage axis for $V_{\rm MR}=10$ V. At room temperature, the subthreshold swing $S \equiv \ln 10\, dV_{\rm GS}/d(\ln I_{\rm DS\ sub}) = \ln 10\, nkT/q$, where n is the ideality factor, is approximately 450 mV/decade of current. This subthreshold swing yields an ideality factor $n=7.5$, which would correspond to a $\rm SiO_2$–Si interface trapped charge density of about $2.1\times 10^{12}\,{\rm cm}^{-2}\,{\rm eV}^{-1}$. Measurements of the interface charge density using the conductance method[11] confirmed this estimate. The measured ideality factor is very large compared to the ideal value $n=1.7$ expected for this structure, and it should be possible to reduce the interface trapped charge density substantially with optimized annealing procedures. These improvements should allow significantly reduced values of subthreshold swing to be attained, resulting in a corresponding improvement in sensor response.

The dependence of the transistor threshold voltage V_T, and thus of the charge $Q_{\rm MR}$, on the current $I_{\rm MR}$ through the magnetoresistive layer is shown in Fig. 3. These data were obtained by a measurement of the threshold voltage shift for a fixed drain-source voltage of -5 V and at a gate-source voltage of -7 V for a series of different currents $I_{\rm MR}$ through the magnetoresistive layer, relative to the threshold voltage for $I_{\rm MR}=0$ A. The threshold voltage increases sharply at small current $I_{\rm MR}$, a behavior which is interpreted as a consequence of the non-ohmic tunnel characteristics of the Al contacts to the magnetoresistive layer for very small applied bias. For larger currents $I_{\rm MR}$, ΔV_T varies linearly with $I_{\rm MR}$ as expected from Eq. (2).

B. Response to externally applied magnetic field

If an external magnetic field H is applied, the current $I_{\rm MR}$ and thus the transistor threshold voltage V_T will change. This

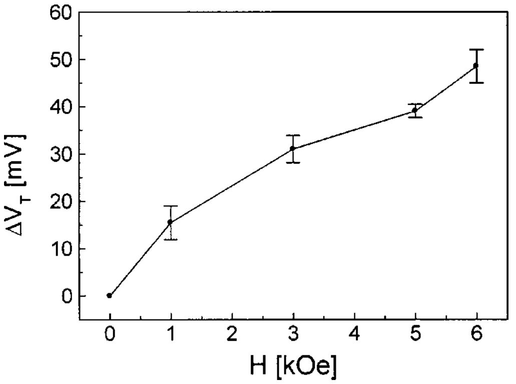

FIG. 4. Shift in transistor threshold voltage ΔV_T as a function of externally applied magnetic field H. The threshold voltage shifts monotonically with H.

effect can be clearly observed in Fig. 4, which shows the shift in threshold voltage relative to the threshold voltage at zero magnetic field measured as a function of magnetic field for a fixed drain-source voltage of -5 V, and a fixed gate-source voltage of -6.9 V. The threshold voltage increases monotonically with magnetic field as expected from Eq. (3), since $I_{\rm MR}$ increases monotonically with magnetic field.

The resulting changes in transistor drain-source currents in the subthreshold regime ($I_{\rm DS\ sub}$) and in the saturation regime ($I_{\rm DS\ sat}$), compared to that in the current $I_{\rm MR}$ through the magnetoresistive layer, are shown in Fig. 5 as functions of externally applied magnetic field H. $I_{\rm DS\ sat}$ was obtained in saturation with $V_{\rm MR}=10$ V, $V_{\rm GS}=-20$ V and $V_{\rm DS}=-20$ V, while $I_{\rm DS\ sub}$ was obtained in the subthreshold regime with $V_{\rm MR}=10$ V, $V_{\rm GS}=-7$ V and $V_{\rm DS}=-5$ V. At $H=6$ kOe, the absolute change in $I_{\rm MR}$ is 60 nA and the relative change in $I_{\rm MR}$ is $\sim 5\%$. In comparison, the absolute change in $I_{\rm DS\ sat}$ from its value for $H=0$ Oe is approximately 30 μA, a factor of 500 larger than the corresponding absolute change in $I_{\rm MR}$. However, the relative change of $<1\%$ in $I_{\rm DS\ sat}$ is small

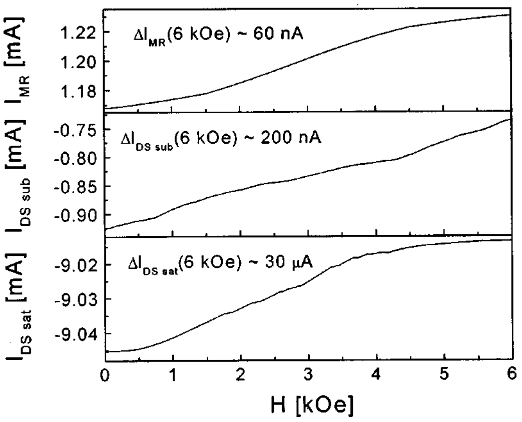

FIG. 5. Absolute response of the current $I_{\rm MR}$ through the magnetoresistive layer, the transistor subthreshold current $I_{\rm DS\ sub}$, and the transistor saturation current $I_{\rm DS\ sat}$ on the externally applied magnetic field. At 6 kOe, the absolute change in $I_{\rm DS\ sub}$ is factor of 3–4 larger than the absolute change in $I_{\rm MR}$, and that in $I_{\rm DS\ sat}$ is a factor of 500 larger.

compared to the relative in I_{MR}. The relative change in drain-source current in the saturation regime is given by[8]

$$\frac{\Delta I_{\mathrm{DS\,sat}}(H)}{I_{\mathrm{DS\,sat}}(0)} \approx \frac{2\Delta V_T(H)}{V_{\mathrm{GS}}-V_T(0)}$$

for

$$\Delta V_T \ll V_{\mathrm{GS}}-V_T(0). \tag{4}$$

Thus, the absolute response in the saturation regime can be further improved by increasing the zero-magnetic field saturation current $I_{\mathrm{DS\,sat}}(0)$ and decreasing the gate-source voltage V_{GS} as well as the threshold voltage V_T, which should be possible with an optimized device design with decreased device dimensions. In addition, the threshold voltage shift could be increased by an optimized TMR film/gate structure. The large signal of 30 μA that arises upon application of the saturation field provides an advantage over sensors which require additional electronics to amplify the sensor signal. Due to the large gain of this device, the sensor signal will be less susceptible to noise that may be picked up during transmission from the sensor to external electronic circuitry.

The absolute change measured in $I_{\mathrm{DS\,sub}}$ is about 200 nA, a factor of about 3–4 larger than the corresponding change in I_{MR}. The relative change in $I_{\mathrm{DS\,sub}}$ is about 20%, corresponding to an amplification in relative sensitivity of a factor of four. The change in $I_{\mathrm{DS\,sub}}$ in our prototype demonstration device is relatively modest due to the large subthreshold swing. For devices with ideality factor n closer to the expected value of 1.7, $I_{\mathrm{DS\,sub}}$ would change by 68% for a p-type device, and the sensitivity would be amplified by a factor of over ten. For an n-type device, $I_{\mathrm{DS\,sub}}$ would change by about 200% and the sensitivity would be amplified by a factor of over thirty. It is anticipated that additional improvements in subthreshold would arise from reduction of device dimensions and from optimization of material characteristics and device geometry.

While the high saturation field of the Co/SiO$_2$ granular-magnetoresistance film limits the low-field sensitivity of this device, very substantial benefits may be realized in sensing of higher magnetic fields. For sensor applications at higher magnetic fields up to about 1 T, Hall bar sensors are usually used, which show a supply-current related sensitivity $S_I = V_H/(I\cdot H)$ typically in the range of 0.07–0.31 Ω/Oe.[12] If the granular Co/SiO$_2$ film employed in our device structure is used as a simple magnetoresistor, we obtain an averaged supply-current related sensitivity $S_I = V_{\mathrm{MR}}/(I_{\mathrm{MR}}\cdot H)$ of about 0.73 Ω/Oe for magnetic fields H smaller than the saturation field. The corresponding value in the subthreshold regime of the device described in this work is given by $S_I = V_{\mathrm{DS}}/(I_{\mathrm{DS}}\cdot H) \approx 250$ Ω/Oe when calculated for $V_{\mathrm{DS}} = -5$ V, which is much larger than the values obtained for Hall bar sensors and could be further increased with the above-mentioned optimization methods. However, our device may be limited by the relatively low current level in the subthreshold regime which could increase susceptibility to noise, and for high-field applications by the saturation field of the magnetoresistive film. This first obstacle could be overcome by additional amplification of the signal. Due to the strong dependence of the coercivity on the particle size in granular magnetic field,[13] the saturation field might be increased by an optimized granular film structures.

IV. CONCLUSIONS

We have presented and analyzed a novel hybrid magnetoelectronic device for magnetic field sensing which is based on the incorporation of a granular tunnel-magnetoresistive film into the gate of a field-effect transistor structure. In this device, the magnetoresistive response of the TMR film in converted to a transistor threshold voltage shift, which results in an improved response in drain-source current of the transistor to an externally applied field compared to the response of the TMR film alone. In our prototype device based on a p-channel MOSFET, a threshold voltage shift of 50 mV was obtained upon application of a 6 kOe magnetic field at room temperature, leading to a fourfold amplification in relative current response, and an increase in absolute current response by a factor of ~500 in the saturation regime, as compared to the response attainable in the magnetoresistive film alone. Reduced device dimensions and improvements in the device fabrication process as well as optimization of the granular TMR material should result in dramatic improvements in device performance. Because of the relatively high saturation fields of granular magnetoresistive films, very substantial benefits may be realized particularly in sensor applications at higher magnetic fields, where this device concept compares very favorably with devices such as Hall bar sensors.

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