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A monolithic field-effect-transistor-amplified magnetic field sensor

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We propose and demonstrate the operation of a monolithic field-effect-transistor-amplified magnetic field sensor device, in which a tunnel-magnetoresistive (TMR) material is incorporated within the gate of a Si metal–oxide–semiconductor–field-effect transistor. A fixed voltage is applied across the TMR layer, which leads charge to build up within the gate. Applying or changing an external magnetic field causes a change in the charge within the TMR layer and, consequently, a shift in the transistor threshold voltage, which leads to an exponential change in subthreshold current $I_{\mathrm{DS\ sub}}$ and a quadratic change in saturation current $I_{\mathrm{DS\ sat}}$. The application of a 6 kOe magnetic field at room temperature leads in our device to an absolute change in $I_{\mathrm{DS\ sub}}$ three times as large and in $I_{\mathrm{DS\ sat}}$ 500 times as large as the corresponding change in current through the TMR layer alone. The relative change in $I_{\mathrm{DS\ sub}}$ is a factor of four larger than that in the current through the TMR layer. © *1999 American Institute of Physics.* [S0003-6951(99)04431-9]

Magnetic field sensors with improved sensitivity at room temperature are highly desirable for a variety of applications, perhaps most notably in future magnetic data storage systems. Approaches for amplification of response based on incorporation of sensor materials into electronic device structures have been developed for a variety of sensor applications. In the spin-valve transistor,[1] a giant-magnetoresistive thin film is incorporated as the base layer in a metal-base transistor. A field-dependent base transport factor then leads to amplified collector current response in the transistor. However, the fabrication of these devices requires vacuum metal bonding, and lithographic processing is difficult. Another approach for amplification of a sensor signal is the incorporation of the sensor material within the gate structure of a field-effect transistor (FET); this concept has been demonstrated in FET-based chemical and gas sensors in which gas or ion adsorption or absorption in the gate structure results in a shift in transistor threshold voltage and, consequently, amplified response in the transistor channel conductance or subthreshold current.[2,3]

In this letter, we describe the design, fabrication, and demonstration of a transistor-amplified magnetic field sensor in which a granular tunnel magnetoresistive (TMR) $\mathrm{Co}_x(\mathrm{SiO}_2)_{1-x}$ thin film is incorporated within the gate of a *p*-channel Si metal–oxide–semiconductor–field-effect transistor (MOSFET) as shown in Fig. 1. The basic concept is, however, applicable to any FET, as well as other magnetoresistive materials in which stored charge associated with electrical current flow is present. The sensor device was fabricated employing a nonself-aligned process acceptable because of the large device dimensions ($50\,\mu\mathrm{m}\times 1000\,\mu\mathrm{m}$ gate). The source and drain regions were formed by boron diffusion into an *n*-type Si wafer ($N_D\sim 2\times 10^{15}\,\mathrm{cm}^{-3}$) with a patterned oxide mask. The 20 nm lower gate oxide was formed by dry thermal oxidation, and Al ohmic contacts were made to the source and drain regions and to the back of the wafer. The magnetoresistive layer, consisting of a 20 nm granular film of volume composition $\mathrm{Co}_{0.41}(\mathrm{SiO}_2)_{0.59}$, was then deposited on the lower gate oxide by cosputtering from separate Co (dc sputtered) and SiO_2 (rf sputtered) sources at room temperature and an Ar pressure of 2 mTorr, followed by a 20 nm rf sputtered SiO_2 layer.[4] Finally, 100 nm Al contacts to the magnetoresistive film and to the gate, source, and drain were deposited by thermal evaporation.

The Co/SiO_2 film consists of Co clusters with an average diameter of about 4 nm, embedded in a SiO_2 matrix.[4,5] 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.[6] In the sensor device structure shown in Fig. 1, a fixed voltage V_{MR} applied across the Al contacts to the Co/SiO_2 layer leads to a current I_{MR} flowing through the TMR film; the typical current levels employed and the resistivities of the Co/SiO_2 granular films suggest that a large fraction of the applied voltage is dropped across the Al

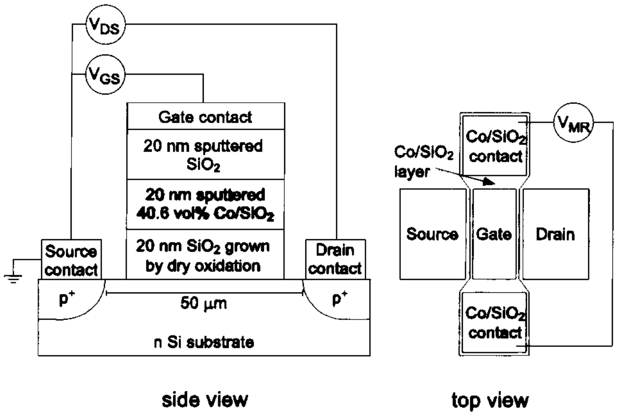

FIG. 1. Schematic diagram of the monolithic transistor-amplified magnetic field sensor device in which a magnetoresistive layer is incorporated within the gate structure of a Si MOSFET.

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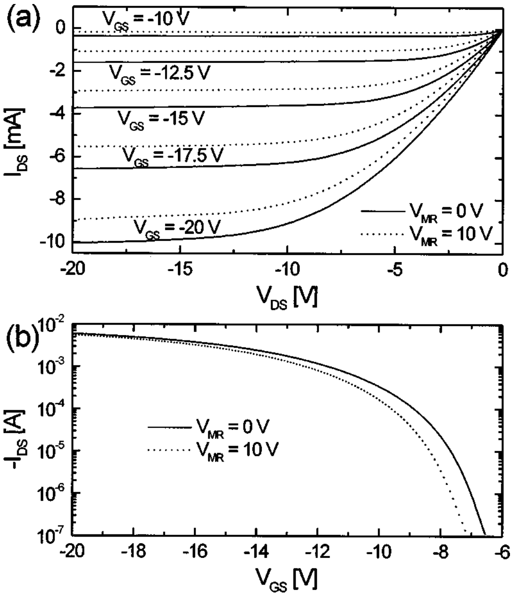

FIG. 2. (a) Transistor current–voltage characteristics for $V_{\text{MR}} = 0$ V and for $V_{\text{MR}} = 10$ V. (b) Subthreshold current–voltage characteristics for $V_{\text{MR}} = 0$ V and $V_{\text{MR}} = 10$ V, showing a clear shift in threshold voltage, which is a result of the presence of stored charge within the gate.

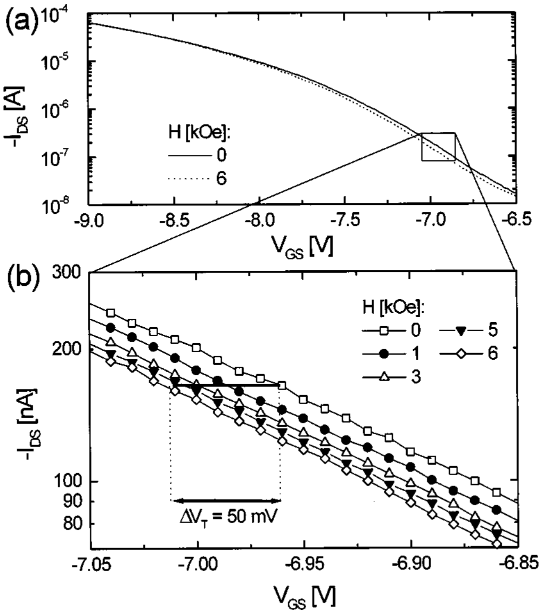

FIG. 3. (a) Subthreshold current–voltage characteristics for $V_{\text{DS}} = -5$ V as a function of externally applied magnetic field *H*. (b) Magnified view of the subthreshold region; application of a 6 kOe field shifts the threshold voltage by 50 mV.

contact/SiO$_2$/Co tunnel junctions, and that within the granular film transport is in the low-field regime.[7]

Charge storage in the TMR layer is believed to occur via the following mechanism. Electrons tunneling from one Al contact into a Co cluster experience a barrier height ϕ_0, where ϕ_0 is the average barrier height of the Al–SiO$_2$–Co barrier, and must provide the single-electron Coulomb charging energy E_C of the Co cluster, while electrons tunneling from Co clusters into the other Al contact release the energy E_C and must overcome a barrier height of $\phi_0 - E_C$. The difference in the tunneling processes results in different time-dependent tunnel currents $I_{\text{in}}(t)$ and $I_{\text{out}}(t)$ into and out of the Co/SiO$_2$ layer, respectively, which leads to stored charge $Q(t)$ in the Co/SiO$_2$ layer. This charge in turn yields voltage drops V across the contacts given by $V(t) = V_{\text{MR}}/2 \pm Q(t)d/2\epsilon$, where d is the barrier width between the Al contact and a Co cluster, and ϵ is the dielectric constant of SiO$_2$. A detailed analysis yields values for the stored charge of the correct sign and close to the experimentally observed values.[8]

Figures 2(a) and 2(b) show, respectively, I_{DS} as a function of the drain–source voltage V_{DS} and the gate–source voltage V_{GS}, and the subthreshold current–voltage characteristics, in both cases for $V_{\text{MR}} = 0$ V and $V_{\text{MR}} = 10$ V. The transistor current–voltage characteristics show that the transistor threshold voltage V_T is a function of the current I_{MR} through the magnetoresistive film. Since the threshold voltage is proportional to the charge Q_{MR} within the magnetoresistive layer, this indicates that the charge Q_{MR} is a function of I_{MR}. I_{DS} decreases upon application of a nonzero voltage V_{MR} across the magnetoresistive layer, corresponding to a positive threshold voltage shift of ~ 0.6 V along the voltage axis for $V_{\text{MR}} = 10$ V. This positive threshold voltage shift corresponds to a positive net charge $Q_{\text{MR}} \sim 3.3 \times 10^8 e$ in the magnetoresistive layer, which is close to the range of values, 0.4–$3.1 \times 10^9 e$, obtained using the theoretical analysis described above. At room temperature, the subthreshold swing $S \equiv \ln 10 \cdot dV_{\text{GS}}/d(\ln I_{\text{DS sub}}) = \ln 10 \cdot nkT/q$, where n is the ideality factor, is approximately 450 mV/decade of current. This corresponds to an ideality factor of $n = 7.5$, which is very large compared to the ideal value $n = 1.7$ expected for this structure. The large subthreshold swing is believed to be a consequence of the relatively poor quality of the Si/SiO$_2$ gate oxide interface and possibly of damage to the lower SiO$_2$ gate layer caused by the sputtering process. Improvements in oxide quality should allow substantially better values of subthreshold swing to be attained, with corresponding improvements in sensor response.

When an external magnetic field H is applied, the Co/SiO$_2$ film resistance and thus the current through the magnetoresistive film change. The charge in the Co/SiO$_2$ film then changes by an amount $\Delta Q_{\text{MR}}(H) \equiv Q_{\text{MR}}(0) - Q_{\text{MR}}(H)$ from the zero magnetic-field charge $Q_{\text{MR}}(0)$, shifting the MOSFET threshold voltage by $\Delta V_T(H) \equiv V_T(0) - V_T(H) = -\Delta Q_{\text{MR}}(H)/C_{\text{ox}}$, where C_{ox} is the capacitance of the upper SiO$_2$ layer in the gate structure.[9] This shift in threshold voltage results in magnetic-field-dependent transistor characteristics in both the subthreshold and saturation regime. The subthreshold drain–source current $I_{\text{DS sub}}$ of the MOSFET depends exponentially on the threshold voltage according to[10] $I_{\text{DS sub}} = I_{0\,\text{sub}} \exp[e(V_{\text{GS}} - V_T)/nkT] \times [1 - \exp(-eV_{\text{DS}}/kT)]$, where $I_{0\,\text{sub}}$ is a constant, k is the Boltzmann constant, e is the electron charge, and T is the temperature. $I_{\text{DS sub}}$ therefore depends exponentially on $\Delta V_T(H)$. The saturation current $I_{\text{DS sat}}$ of the MOSFET can be approximated by $I_{\text{DS sat}} \approx I_{0\,\text{sat}}(V_{\text{GS}} - V_T)^2$, where $I_{0\,\text{sat}}$ is a constant. The relative change in $I_{\text{DS sat}}$ as a function of H for $\Delta V_T(H) \ll V_{\text{GS}} - V_T(0)$ is then given approximately by $|2\Delta V_T(H)/(V_{\text{GS}} - V_T(0))|$.

The dependence of the transistor current–voltage characteristics on an externally applied magnetic field is shown in Fig. 3. A constant voltage $V_{\text{MR}} = 10$ V was applied across

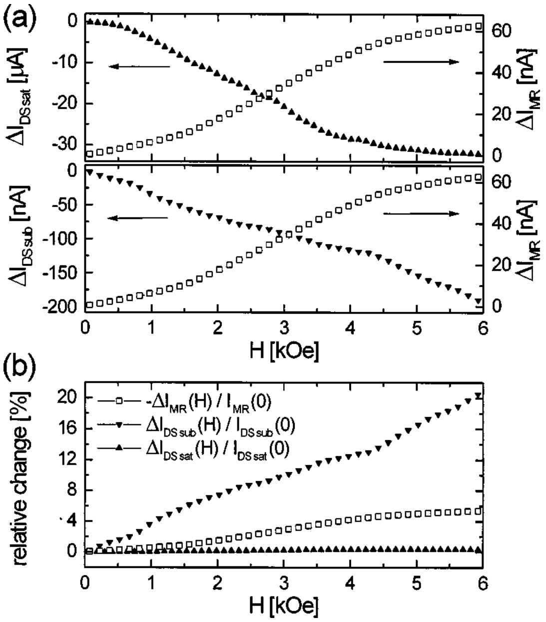

FIG. 4. (a) Absolute change in the saturation current $I_{DS\,sat}$ and in the subthreshold current $I_{DS\,sub}$, and the current I_{MR} in the magnetoresistive layer as a function of externally applied magnetic field *H*. (b) Relative change in $I_{DS\,sat}$, $I_{DS\,sub}$, and I_{MR} as a function of *H*. The field sensitivity increases by a factor of about 4 in the subthreshold regime.

the magnetoresistive layer, and V_{DS} was fixed at -5 V. All measurements were obtained at room temperature. The data in Figs. 2 and 3 show clearly that current flow through the magnetoresistive layer and application of an external magnetic field produce shifts in threshold voltage, rather than simply increasing the leakage current. The maximum threshold voltage shift from zero magnetic field to the saturation field H_{sat} of the magnetoresistive layer (about 6 kOe) is approximately 50 mV. Decreasing the device dimensions, i.e., gate length and width, will allow operation at lower voltage and current levels. In addition, optimizing the magnetoresistive layer characteristics and overall gate structure, should also increase the threshold voltage shift arising from application of an external magnetic field, thereby resulting in larger amplification factors.

Figure 4(a) shows the absolute change in $I_{DS\,sat}$ and $I_{DS\,sub}$ compared to the independently measured current I_{MR} through the magnetoresistive layer alone upon application of the magnetic field *H*. $I_{DS\,sat}$ was obtained in saturation with $V_{MR}=10\,\mathrm{V}$, $V_{GS}=-20\,\mathrm{V}$, and $V_{DS}=-20\,\mathrm{V}$, while $I_{DS\,sub}$ was obtained in the subthreshold regime with $V_{MR}=10\,\mathrm{V}$, $V_{GS}=-7$ V, and $V_{DS}=-5$ V. The currents at zero magnetic field are $I_{DS\,sat}=-9$ mA, $I_{DS\,sub}=-0.925\,\mu\mathrm{A}$, and $I_{MR}=1.17\,\mu\mathrm{A}$. At 6 kOe, the absolute change in $I_{DS\,sat}$ is approximately 30 μA, a factor of 500 larger than the corresponding change in I_{MR} of about 60 nA. However, the relative change in $I_{DS\,sat}$, shown in Fig. 4(b), is less than 1%.

At 6 kOe, the absolute change in $I_{DS\,sub}$ is about 200 nA, corresponding to a relative change of about 20%. Compared to the relative change in I_{MR} of about 5%, this shows an amplification in sensitivity of a factor of 4. The change in $I_{DS\,sub}$ is relatively modest due to the large subthreshold swing exhibited by the prototype device. For devices with ideality factor *n* closer to the expected value of 1.7, $I_{DS\,sub}$ would decrease by 68%, an amplification in sensitivity by a factor of over 10.

In summary, we have proposed, experimentally demonstrated, and analyzed a novel monolithic transistor-amplified magnetic-field sensor. Incorporation of a granular metal/insulator magnetoresistive film into the gate structure of a FET allows the magnetoresistive response to be converted to a shift in the threshold voltage of the transistor, resulting in a large amplification in sensitivity to an external magnetic field. In a prototype device based on a *p*-channel MOSFET, a threshold voltage shift of 50 mV upon application of a 6 kOe magnetic field was obtained at room temperature. This resulted in 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 and layer structure, should result in dramatic improvements in device performance.

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