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Magnetic read-only memory with removable medium

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A solid-state memory concept is discussed, featuring a removable data carrier on which information is stored in a pattern of magnetic bits. The information is read out with a sensor array of magnetic tunnel junctions. The calculated readout signals of the sensors are compared with the measured values for a magnetic card with a data density of 0.5 Mbyte/cm². The card-sensor separation is identified to determine the ultimate achievable data density. © 2005 American Institute of Physics.

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At present, the most abundant types of data storage are magnetic disk storage, optical disk storage, and solid-state storage. For content distribution to portable devices, a low-cost storage concept could be of interest. Such a storage solution should combine the removability and replicability of magnetic disk storage, optical disk storage, and solid-state memory. However, the information is not stored in the array itself but contained on a separate and removable data carrier. Together, the reader and data carrier form a magnetic read-only memory (MROM).

As sketched in Fig. 1, the binary information on the MROM card is encoded into the topography of the medium via mesas of a ferromagnetic material. For our experiment we produced data carriers on glass substrates, on which a pattern of 100-nm-high mesas was created in resist using e-beam lithography. The rectangular footprint of a single bit measures $1 \times 5 \: \mu m^2$, the pitch being 4 and 7 $\mu m$ in the x and y direction, respectively, as indicated in the right panel of Fig. 2. This corresponds with a bit density of 0.5 Mbyte/cm². The medium was completed by sputter deposition of 200 nm Co$_9$Fe$_{10}$ through a shadow mask while applying a magnetic field in the y direction. After the processing the glass plate was sawn into pieces of $6 \times 4 \: mm^2$.

The magnitude of the field generated by a bit is calculated analytically by solving the magnetostatic Maxwell equations for a single-domain particle (cuboid) uniformly magnetized in the y direction. The sensor is only sensitive to the magnetic field component in the y direction, which for a single cuboid is

$$H_y(x,y,z) = \sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{k=0}^{1} (-1)^{i+j+k} \frac{M_{\text{bit}}}{4\pi} \times \arctan \left( \frac{(x-a)(z-c)}{(y-b)\sqrt{(x-a)^2 + (y-b)^2 + (z-c)^2}} \right) ,$$

where $M_{\text{bit}}$ (8.7 kOe) is the magnetization of the Co$_9$Fe$_{10}$ film. $a = w_{\text{bit}}(i - \frac{1}{2})$, $b = t_{\text{bit}}(j - \frac{1}{2})$, $c = t_{\text{bit}}(k - \frac{1}{2})$ and $w_{\text{bit}} = 1 \: \mu m$, $t_{\text{bit}} = 5 \: \mu m$ and $t_{\text{bit}} = 100 \: nm$ are the width, length and topographical height of the cuboid, respectively. The center of the cuboid is taken as the origin of the x, y, z coordinates. Because the CoFe layer is covering the mesas as well as the substrate, the magnetic field of a single bit is the sum of two cuboids. One is on top of the mesa, whereas the other is translated in the z direction with 200 nm and has an opposite magnetization direction.

To read out the local magnetic fields of the bits we developed a dedicated sensor array of $3 \times 3$ elements, as shown in the left panel of Fig. 2. The dye size of the sensor chip measures $7 \times 7 \: mm^2$, its processing has been described elsewhere. A magnetic tunnel junction (MTJ) is located at each crossing of a word and bit line. The two ferromagnetic layers of the MTJ were magnetized in a so-called crossed anisotropy geometry in order to linearize the output signal of the sensor. The sensitivity of the sensor elements was measured to be in a narrow range of $6 \sim 8 \: \Omega/Oe$. We can use the Stoner–Wohlfarth (SW) model for the magnetization rotation of the free magnetic layer in the MTJ, to calculate the sensitivity. As the length of the free layer electrode is much larger than its height and width, the SW model approximately yields

$$\frac{\partial R_{\text{MTJ}}}{\partial H} \bigg|_{H=0} \approx \frac{\Delta R}{M_f} \frac{w_f}{2M_f t_f} ,$$

where $\Delta R$ is the difference in resistance of the MTJ between its parallel and antiparallel state, $M_f$ is the magnetization of the free layer in the MTJ, and $w_f$ and $t_f$ are the width and thickness of the free layer of the MTJ. The MTJs had a resistance $R_{\text{par}}$ in the parallel state in the range of 5.5–8.5 kΩ, and an MR ratio of 20%, $M_f = 17 \: kOe$, and the dimensions of the free layer are $t_f = 5 \: \mu m$, $w_f = 1 \: \mu m$ and $t_f$
However, no oscillations in the array were read out in parallel, nine identical images with a translational shift over the sensor pitch distances were obtained, without any mutual interference.

To allow for a more detailed comparison between the measured and calculated signal, we collected line scans measured by a single MTJ. Several line scans for different \( z \) values were taken in the \( y \) direction: see Fig. 5. In this case a different medium was used, having bits at every site. To mimic the averaging effect of an MTJ sensor of \( 5 \times 1 \) \( \mu \text{m}^2 \) on the measured signal, the calculated magnetic field was taken as the average of 35 points, 7 in the \( x \) direction and 5 in the \( y \) direction. This proved to be a sufficient dense mesh for reliable averaging. As shown in Fig. 5, the measured signal oscillates over a range of \( \sim 20 \) Oe, whereas the calculated signal oscillates over a range of \( \sim 10 \) Oe. Both have a period of 7 \( \mu \text{m} \) and both have a tooth-like shape. The twin peaks in the measured signal are closer together than the calculated ones while the valleys are wider. This indicates that the magnetic poles of the bits are not at the edges of the bits but translated slightly inwards, which is to be expected when energetically favorable domains form at the short sides of the bit. Yet, the overall agreement between measured and calculated signal shows that the magnetic field description of the bits according to \( \text{Eq. (1)} \) is a useful approximation.

The line scans for different medium-sensor distances allow us to analyze the decay of the measured signal with the separation distance. To describe this decay for a periodic array of magnetic bits as a function of sensor-medium distance, it is convenient to use Fourier analysis. The decay of

\[
\text{Eq. (1)}
\]

for clarity, not all measured scans are shown. The bold line represents the magnetic field calculated with \( \text{Eq. (1)} \) for \( z=0.95 \) \( \mu \text{m} \). The lateral step size was 0.167 \( \mu \text{m} \).
the magnetic field signal of a bit surrounded by other bits, as a function of the sensor-bit distance, may then be described by the following equation:

\[ H_y(z) = H_0 e^{-\frac{z}{k_x^2 + k_y^2}}, \]  

(3)

where \( H_0 \) is the coefficient of the Fourier component with the highest spatial wave numbers \( k_x \) and \( k_y \). Since the length of the MTJ element is larger than the pitch of the bit pattern in the \( x \) direction, the highest wave number in the \( x \) direction is in fact averaged out: \( k_x = 0 \). Therefore, in our experiment the exponent in Eq. (3) transforms to \(-0.90 \cdot z \) (\( z \) in \( \mu m \)). The corresponding Fourier component can be calculated from Eq. (1) by a discrete Fourier transformation of the field of a single bit,\(^7\) from which \( H_0 = 7.2 \) Oe is obtained. Inserting this value in Eq. (3) yields the line plotted in Fig. 6; also plotted are the data points extracted from Fig. 5. For the larger separations there is a good match between the measured and calculated curve, while at smaller distances the differences are within a factor 2. Figure 6 clearly shows that the Fourier analysis correctly describes the decay of the bit signal as a function of the sensor-medium separation distance \( z \), without any additional fit parameters.

This allows us to estimate how much the bit density may be increased considering the experienced shortest sensor-medium distance of 0.93 \( \mu m \) under ambient conditions as a strict limitation. With the same magnetic material but increasing the height of the mesas in the topography of the medium from 100 to 500 nm, we can increase \( H_0 \) in Eq. (3) to 17 Oe. Assuming that signals of a tenth of the magnitude shown in Fig. 5 are still detectable and that a tenfold more sensitive MTJ is available, we recalculated \( k \) for a square bit using Eq. (3). The value thus obtained corresponds to 5 Mbyte/cm\(^2\) as maximum achievable bit density.

In conclusion, a MROM concept is discussed featuring a removable data carrier with prerecorded magnetic bits. We show that medium cards with a density of around 0.5 Mbyte/cm\(^2\) can be read out. The critical scaling parameter is the medium-sensor separation distance, as the signal decays exponentially with this distance.


