Switching in spin-valve devices in response to subnanosecond longitudinal field pulses

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We have fabricated spin-valve devices in a high-speed test structure that allows subnanosecond pulsed field excitation and high-bandwidth observation of the magnetoresistance response. The switching response varies for low-amplitude field pulses and approaches a consistent fast switch of less than 1 ns for field pulses of higher amplitude. For several pulse widths and amplitudes, the device switches into metastable states. The threshold amplitude of the write-pulse was measured as a function of pulse duration for pulses as small as 250 ps in duration. [S0021-8979(00)55408-5]

INTRODUCTION

Studies of the dynamics of the magnetization rotation and reversal process in submicrometer giant magnetoresistive (GMR) devices are becoming important due to their applications in nonvolatile memory arrays.[1] Magneto-optical and inductive techniques[2] have proven very successful in tracking the magnetization dynamics in thin films; however, their usefulness is limited in the measurement of submicrometer structures. Magnetic-force microscopy and other imaging techniques can show fine magnetic structure in very small devices, but they are too slow to follow the actual dynamics as the device responds to external fields. The most common way to study the evolution of the magnetization in GMR devices has been through micromagnetic simulations.[3,4] We present here a method to physically measure the dynamics of components of the average magnetization in submicrometer sized devices.

EXPERIMENT

Our experimental technique allows observation of the GMR signal in the subnanosecond time domain. A test structure that has been discussed previously[5] was fabricated that incorporates high-bandwidth microstrip write- and sense-line waveguide structures on the same chip as the device being tested. This allows the device to be exposed to subnanosecond field pulses along the long direction of the device, and it allows the observation of the response of the device, resolved on the same time scale. One modification made to what was earlier reported is a wider, 4 μm write-line which provides the device with a spatially more uniform field over the device.

The device measured is a spin-valve using a synthetic antiferromagnet (SAF) pinning structure.[6] The films were sputter-deposited in an Ar plasma into the following structure: Ta(5.0)–$Ni_{0.8}Fe_{0.2}$(2.0)–Co(1.0)–Cu(3.0)–Co(2.0)–Ru(0.6)–Co(1.5)–FeMn(10.0)–Ta(5.0), where the thicknesses are given in nm. We have measured a pinning field that exceeds 80 kA/m (1000 Oe), which provides reasonable assurance that the magnetization of the pinned layer is immobile while the device is exposed to external fields. Additionally, the low net moment of the SAF corresponds to minimal magnetostatic interactions between the free layer and the pinned layer. The device is an optically patterned rectangular structure with rounded ends. Its width is about 0.9 μm and its length is 4.8 μm. The resulting shape anisotropy dominates the low-frequency response to the longitudinal field, giving a switching field of 2.6 kA/m (33 Oe). The hysteresis loop is additionally shifted to the aligned state by a field of about 0.88 kA/m (11 Oe). The GMR of the device is 6.5%, and the pinned layer direction is fixed along the long axis (easy axis) of the device. The sense line leads overlap and electrically short the ends of the device leaving an active area that is 0.9 μm by 1.8 μm. The resistance is proportional to the average longitudinal magnetization of the device active area. The resistance of the device is measured using a constant current of 1 mA through the sense-line. This sense-current generates a small field (sense field) at the free layer that is less than 0.25 kA/m (3 Oe). A magnetization-resistance loop of the device is shown in Fig. 1.

Field pulses, provided by an electronic, high-speed pulse generator, have a fixed amplitude of 10 V, and the duration can be adjusted continuously between 100 ps and 10 ns. The pulse's 10%–90% risetime is 50 ps. The amplitude of the pulse is set using variable attenuators. The write-pulses emerging from the attenuators are sent through a series of switches, through the write-line and finally are input to an oscilloscope. The switches allow the reversal of the current path through the write-line, which results in reversal of the field polarity at the device. A digitizing oscilloscope with a bandwidth of 1.5 GHz and a sampling rate of 8×10^9 samples per second is used, allowing a subnanosecond resolution of the signal in real time (single shot).

We measured the minimum amplitude of the write-pulse required to switch the device as a function of the duration of the write-pulse and the applied transverse bias. A switching event is a 180° reversal of the magnetization of the free layer, made visible as a change in resistance from the low to

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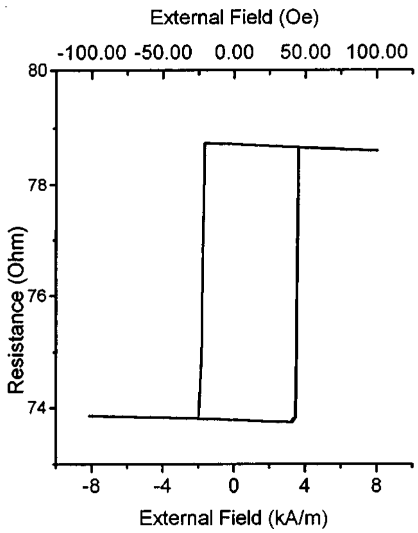

FIG. 1. MR response for spin-valve device. The switching field is 2.6 kA/m (33 Oe) and the interlayer coupling gives a ferromagnetic shift of 0.88 kA/m (11 Oe).

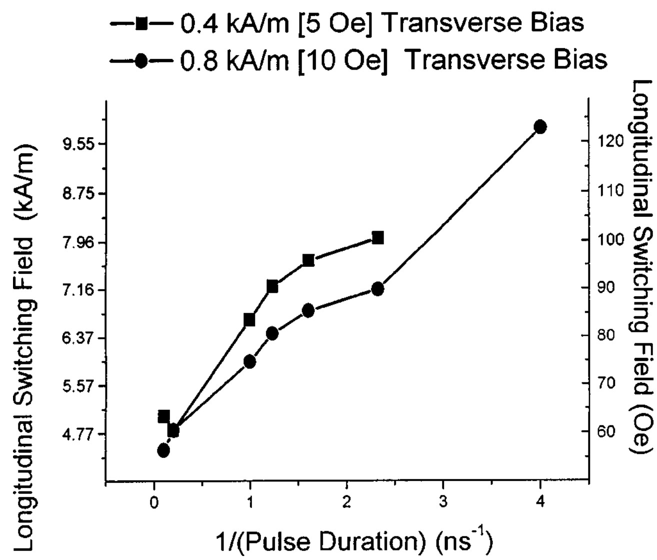

FIG. 2. Switching threshold for pulsed write-fields. Threshold write-pulse amplitude as function of the reciprocal of the write-pulse duration.

high state, or vice versa. The device is prepared in the high state by subjecting it to a continuous train of unattenuated, 10 ns pulses at a repetition rate of 100 kHz for roughly 1 s. The dc resistance of the device is measured to verify that the device is in the high state. The field polarity is then changed by reversing the current path through the write-line, and the pulse duration and amplitude are set. A single pulse is launched, and the resistance of the device is observed following the pulse to see whether a switch occurred. This process is repeated 50 times for each pulse setting. The changes in the resistance of the device associated with the response to the write-pulse is measured in real time on the digitizing ocilloscope.

RESULTS AND DISCUSSION

Switching was observed for write-pulses of durations varying from 0.25 ns to 10 ns. In addition, a transverse bias field was applied from external Helmholz coils in the same direction as the free layer sense field, and it was set at 0.4 kA/m (5 Oe) and 0.8 kA/m (10 Oe). Given these parameters, data were collected for pulse amplitudes stepped through a range beginning at the point where a small change in resistance in the device is seen, and ending well past the switching threshold where the free-layer magnetization consistently switches. A full device switch corresponds to a drop in resistance of about 5 Ω.

For a given transverse bias and write-pulse duration, the device does not reliably switch until the pulse amplitude exceeds a certain threshold value. This amplitude forms a boundary across which the device's switching properties change. At field amplitudes lower than, but near, the switching threshold, the device shows unstable behavior. Sometimes the device resistance is unchanged; sometimes the resistance changes by 0.2 Ω to 1.8 Ω, indicating a high-resistance metastable (HM) state; and occasionally the device switches completely. The HM states correspond to multidomain states, where between 4%–35% of the magnetization within the device active area has switched over. Micromagnetic simulations show that the device response to the external field starts at the edges, and so it is highly likely that a larger proportion of the free-layer magnetization of the entire device has switched.

Increasing the amplitude of the write-pulse to the threshold region causes the free layer to reverse into either a fully switched state or to one of two almost switched, low-resistance metastable (LM) states characterized by a resistance that is 0.5 Ω or 0.15 Ω greater than the resistance of the fully switched state. Switches to the LM states occur in some fraction of the total number of writing events, and this fraction varies depending on pulse parameters and transverse bias fields. Moreover, the reproducibility in the appearance of these states provides evidence that they form as the result of the pinning or trapping of microdomains at specific defects in the device. The link between domain nucleation and growth due to defects has been observed previously in magnetic thin films.[7]

A plot of the amplitude of the threshold write-pulse as a function of the reciprocal pulse duration is shown in Fig. 2. The threshold is determined by the requirement that at least 90% of the device active layer magnetization must switch due to a single write-pulse. As expected, the amplitude needed to switch the device increases as the pulse duration is decreased, and this switching threshold is lower for a higher transverse bias.

The time evolution of the switches shows considerable variety and structure in the way that the resistance falls, depending on the write-amplitude. Figure 3 shows an example of both a fast and slow process switch that occured in response to a 1 ns write-pulse near threshold amplitude. The fast switch occurs in less than 1 ns, whereas the slow switch takes about 5 ns to complete. The slow switch is composed of a fast drop in resistance of roughly 60% and then a much slower remaining drop. This switching structure is indicative of a reversal process more complicated than single domain rotation. Micromagnetic simulations show reversals where

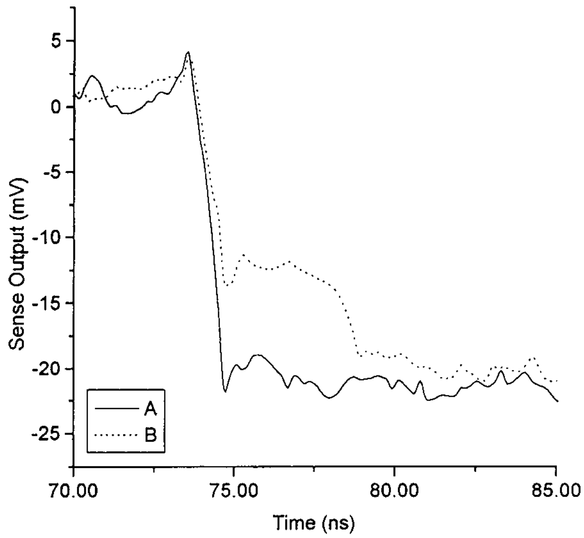

FIG. 3. Time evolution of the sense voltage for a switch around the switching threshold. Curve A shows a fast switch process, and curve B shows a more complex slow process. Write-pulse duration is 1 ns.

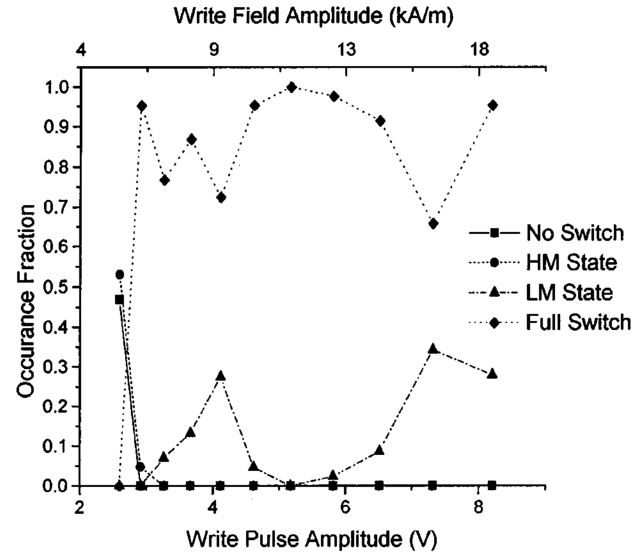

FIG. 4. Occurrence fraction of specific switch result as a function of increased write-pulse amplitude; 0.6 ns write-pulse duration, 0.8 kA/m (10 Oe) applied transverse bias field.

the center of the device switches with a fast rotation while the edges slowly reverse.[8,9] Here, the slow process is a significant component of the switch and may be related to more than just device edges, but including thermally activated switching of domains that are trapped due to defects. For pulse amplitudes at least 2 dB greater than the threshold value, the time response of the resistance drop becomes exclusively that of the fast switch process with fall times of about 500 ps. This indicates a consistent switching with a reversal that is probably due mostly to coherent rotation.

Over the range of write-pulse durations examined, the number of reversals to the fully switched state as a fraction of the total write-events shows a repeated peak and valley trend as the the write-amplitude is increased. This is shown in Fig. 4 for a pulse width of 0.6 ns, but the data for other pulse durations also show this trend. The oscillatory behavior in the number of complete switch events may indicate a separation of regions in write-pulse amplitude where the switching response of the device changes. Simulations have shown that the mechanism for switching for small devices at low switching fields is by the growth of domains propagating inward from the device ends.[3] The first peak may correspond to the threshold write-amplitude for a switch by domain-wall motion, while the second peak may be indicative of the faster, energetically more costly switch dominated by coherent rotation. The dips in complete switch fraction following the peaks are accompanied by peaks in the fraction of switches to the LM state. It is possible this occurs due to excess energy in the device after the switch occurs. This can add disorder to the final state magnetization in the form of short-wavelength excitations that would decay into either the fully switched state or the LM state. The enduring LM states are important to characterize because they affect the device's rereversal process.

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