Current Density Limitations of Spin Valves

Terry J. Gafron, Susan L. Burkett, and Stephen E. Russek

***Abstract*—As spin valve technology evolves, understanding the limitations and design constraints is a critical consideration. Choosing the correct materials combination, aspect ratio and size depends upon careful device characterization. Analysis of spin valves in this study shows that device lifetime and durability are determined by allowable current densities and the internal temperatures that result. Parameters such as maximum sustained current and device degradation can be predicted and calculated, allowing the designer to choose the correct parameters for a specific application.**

***Index Terms*—Current density, lifetime, magnetoresistance, spin valves.**

I. INTRODUCTION

SMALL spin valve devices are susceptible to damage from high current densities during prolonged operation and electrostatic discharge (ESD) events [1]. Irreversible changes are the result of internal device heating and electromigration. In this paper, we examine the stability of spin valve devices when the substrates are kept at low temperature (77°K). The low substrate temperature allows application of large current densities with lower levels of device heating. It is then possible to directly determine if device failure is correlated with the applied current density or with the device temperature. Despite the low substrate temperature, the devices could only be heated to internal temperatures of approximately 540°K by the applied current before catastrophic failure occurred. We found only small changes in device resistance and magnetoresistance for all current densities in which the device temperature was less than 500(K and the applied current level was maintained for short intervals (less than 15 minutes). Irreversible changes were observed in device resistance and magnetoresistance for all current densities in which the device temperature was greater than 500°K and the applied current level was maintained for longer intervals (greater than 8 hours). Thermal runaway occurred at the device failure point.

II. EXPERIMENTAL TECHNIQUES

Spin valves were fabricated by dc magnetron sputter deposition on silicon substrates. Film thickness was controlled from known deposition rates and specific time intervals for each material. The samples were then fabricated using standard sputter deposition techniques with the following layered structure: $Ta_{5.0}$/$NiFe_{5.0}$/$Co_{1.0}$/$Cu_{3.0}$/$Co_{3.0}$/$Ru_{0.6}$/$Co_{2.0}$/$FeMn_{10.0}$/$Ta_{5.0}$, where the subscripts denote the layer thickness in nanometers.

Manuscript received February 14, 2000. This work was supported in part by the National Science Foundation under Grant ECS 9896128 and EEC 9820448.

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Publisher Item Identifier S 0018-9464(00)08940-8.

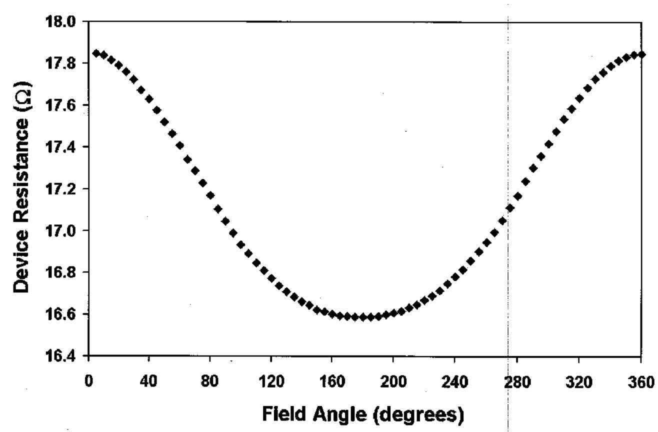

Fig. 1. Determination of the free layer and pinning layer alignment by measuring the magnetoresistance while rotating the device in an 8 kA/m magnetic field.

The films were deposited with a magnetic field applied parallel to the substrate surface to align both the pinned and free layers. The wafers were then patterned using standard optical lithographic techniques and ion beam etching to provide devices of varying geometries and aspect ratios. Arrays of devices were fabricated so that the long axis was either parallel or perpendicular to the orientation of the pinned and free layers. The Ta deposition on the silicon wafer provides a seed layer for the spin valve while the Ta at the end of the deposition sequence acts as a capping layer to protect the FeMn from corrosion. The synthetic antiferromagnet is composed of Co/Ru/Co/FeMn and comprises the pinned layer. The inclusion of Ruthenium has been shown to reinforce the stability of the synthetic antiferromagnet [2] and increase H_p beyond typical values generated by thin films not utilizing Ruthenium [3]. Alignment of the pinned and free layers was determined experimentally by rotating the sample 360° in a constant stationary magnetic field of 8 kA/m while measuring the resulting magnetoresistance with a four-point probe technique.

Fig. 1 shows that the minimum magnetoresistance is obtained at an applied field orientation of 180° for a 16 micrometer device. This indicates nearly an exact alignment between the free and pinned layers of the device. The typical range of resistance for these devices was between 16 Ω and 20 Ω at 300°K. The typical range of $\Delta R/R$ was between 5% and 7% at 300°K. The effective ferromagnetic exchange coupling was between 0.4 kA/m and 0.6 kA/m at 300°K.

III. EXPERIMENTAL RESULTS

Spin valves of 10:1 aspect ratios, and widths from 1 micrometer to 16 micrometers were manually wire-bonded to a probe card with gold wire on a heated vacuum stage. Au is a preferred

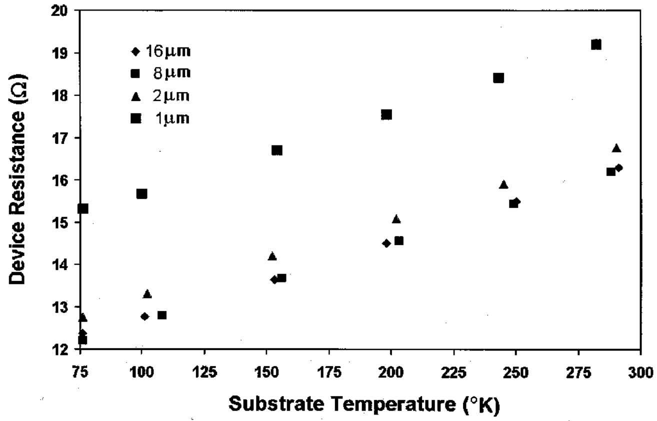

Fig. 2. Device resistance as the substrate was cooled from 300°K to 77°K with an applied magnetic field of 8 kA/m.

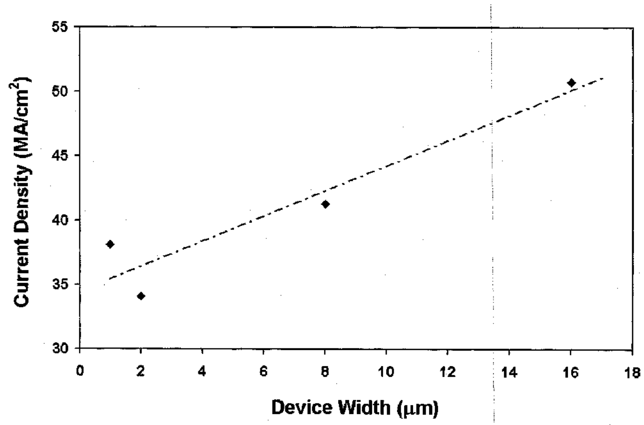

Fig. 4. Current densities that result in device failure for each spin valve stripe width tested.

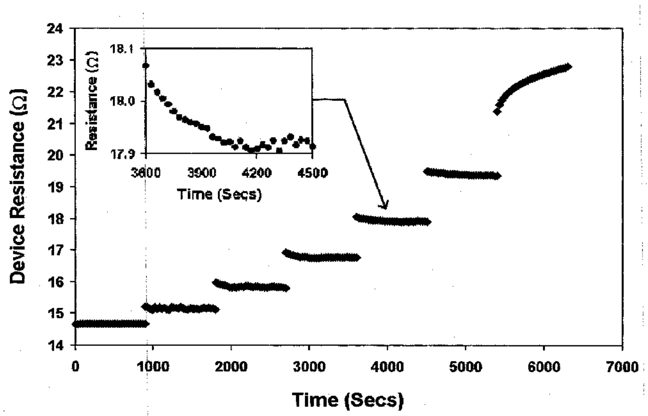

Fig. 3. Device resistance versus time for an increasing applied current (Initial current level = 2 mA, increment = 2 mA). The inset is a close-up of the initial resistive increase and subsequent decrease within the 1 μm device.

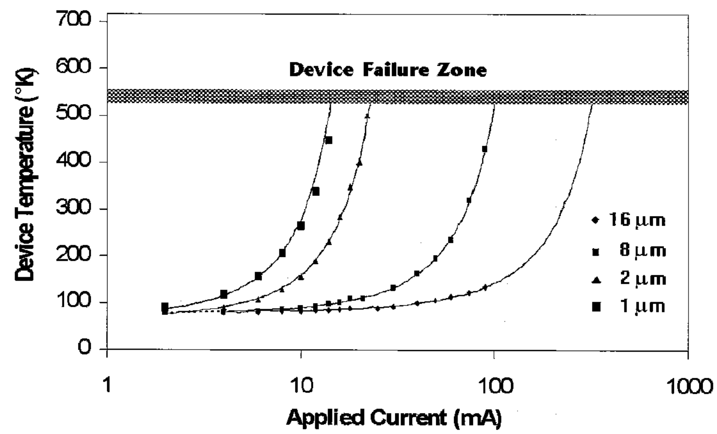

Fig. 5. Internal device temperature as generated by an applied current for each device size tested.

material for work involving high current densities. A comparative study between Au, Cu, and Ag showed the best results are obtained with Au [4]. Au wires can support currents of several Amperes with current densities in excess of 108 A/cm^2. An external magnetic field (8 kA/m) was applied to insure each device was oriented in the parallel state and operating in the saturation region. Using a four-point probe technique, device resistance was recorded as a function of temperature for each device geometry, while the sample was cooled from room temperature to 77°K. Measured saturation resistance as a function of substrate temperature has been shown to be a reliable method for determining internal device temperature [5]. The resulting saturation resistance as a function of substrate temperature is shown in Fig. 2. This technique allows prediction of internal device temperature based upon resistance measurements during test conditions.

Once the device under test has been cooled to 77°K, a constant current is applied. The current level is sustained for a period of 15 minutes to allow the spin valve to stabilize while device resistance is monitored. The applied current bias was used to generate the four-point resistance measurement. An example of device resistance as a function of time and applied current is shown in Fig. 3. The current level is then increased. As current levels increase, device heating occurs and consequently resistance increases. It is interesting to note that an increased current level causes an initial increase in device resistance which slowly decays to a stable, yet elevated value as shown in the inset in Fig. 3. This illustrates the difficulty associated with determining absolute failure points and suggests that the multilayers may undergo atomic mixing due to increased heating before order is established. Magnetoresistive loops are generated at each current step to assess the operation of the device. This cycle is repeated until device failure is reached. Failure is identified by either an unbounded resistance through the structure or by the absence of the magnetoresistive effect. The failure points are indicated in Fig. 4. These failure points determine the extent to which we may current stress the devices. The large variation from the trendline for the small devices is a result of the increased difficulty in determining absolute failure points for smaller dimensions. Small devices fail abruptly at very small current increments, which results in a less accurate determination of the failure points. This failure point information is useful for reliability and performance testing.

A direct correlation between internal device temperature and applied current within the spin valve is indicated. Using exponential curve fitting techniques, we can use the curves in Fig. 5 to predict internal device temperatures based upon applied current levels for each specific device geometry and aspect ratio. These curves may then be translated to other devices of varying geometries but with similar compositions and aspect ratios to predict internal device temperatures and operating limitations. All devices tested experience catastrophic failure at internal temperatures of between 525°K and 550°K. This failure zone is noted in Fig. 5.

For a simple device failure analysis, a spin valve would simply cease to operate at a specific current density. As will be noted, the devices tested suffer gradual performance degradation as they approach the failure zone. The absolute point of device failure as indicated by an unbounded resistance would be represented as the point where each curve becomes asymptotic. Fig. 5 demonstrates that catastrophic failure at internal device temperatures found experimentally, as indicated by the failure zone, are slightly less than those expected to occur at the vertical asymptotes of each curve. Due to the nature of the thermal response of the devices to increasing current levels, locating the exact failure point is difficult and will be the focus of further study.

Approximate failure points of devices, as found experimentally, were used to define operating regions for durability testing. Devices of varying geometries were wire-bonded, tested for magnetoresistance, and cooled to 77°K. Applied current levels were chosen to approximate a 50%, 75%, and a 90% maximum allowable limit. Devices were maintained to operate saturated in the parallel state with an applied field of 8 kA/m. A ramping strategy was used in which each device was operated at 50% maximum for a period of 8 hours, then increased to 75% for 8 hours, and finally operated at 90% maximum for 8 hours. Magnetoresistive measurements were taken before increasing the operating current level. Each device was allowed to settle for 15 minutes to eliminate unwanted transients before initiating magnetoresistive measurements. Several devices showed a slight but gradual decline in magnetoresistive performance.

As shown in Fig. 6, device performance decays rapidly with the initial application of current and then stabilizes as current levels increase. This behavior was typical of many devices tested and is consistent with initial burn-in strategies widely observed in the semiconductor industry [6].

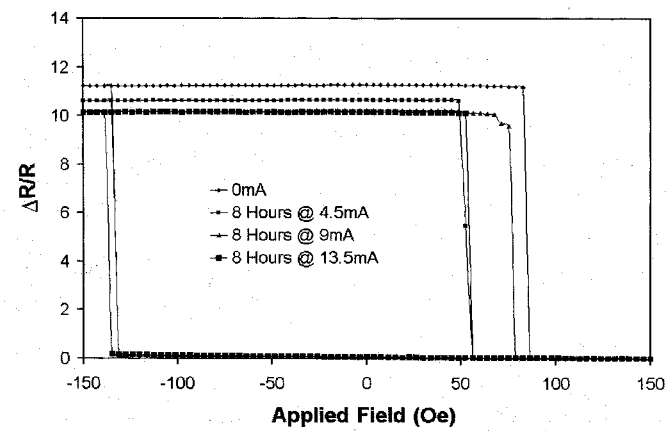

Fig. 6. Magnetoresistive decay of a 1 μm device due to sustained current stress while the substrate was maintained at 77°K.

IV. Conclusion

Spin valves have been tested in a liquid nitrogen environment in an attempt to separate effects of heating and high current densities. Our data indicates that device failure was correlated with thermal runaway even at low substrate temperatures which allowed considerably higher current densities for a given device temperature. Several factors such as bonding pad material and coverage, substrate type, wafer contact surface area and surface area to volume ratios affect heat dissipation and ultimately the maximum allowable current density. For a specific device composition and design, temperature characteristics can be extracted using the device saturation resistance. The temperature data can then be fit to accurately predict the failure point. This information can then be used to determine design constraints for specific spin valve applications.

Acknowledgment

The authors wish to thank the Electromagnetic Technology Division of the National Institute of Standards and Technology for the use of their facilities and equipment.

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