Chapter 11

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ELEG/PHYS667 Magnetism & Spintronics
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In tunnel magnetoresistance, all the properties of the spintronics device under study are determined solely by the interfaces between ferromagnetic electrode and the tunnel barrier, and the details of the barrier itself. One could wonder, what happens to the electrons once they tunnel into otherwise empty states in the anode? They will travel some distance into the metal film before scattering and thermalizing to the Fermi energy. The important observation here is that since the electrode is ferromagnetic, the DOS is spin-dependent, leading to an assymetry in scattering rates for different spin species. In other words, electrons of one spin will travel farther than the other.

This opens up an opportunity for devices which operate via *hot electron* transport in the FM films; if we can collect the hot electrons before they are lost via inelastic scattering and thermalization to the Fermi sea, we can make use of the fact that they have been spin polarized by their transport through the FM. This is analogous to the polarization of light by an optical polarizer: photons with electric field polarization perpendicular to the polarization axis are absorbed, and the beam emerging on the other side is effectively polarized.

But how to collect the hot electrons? we can use an energetic barrier on the far side of the FM that will not accept electrons that have energy lower than the barrier height. For this purpose, a convenient barrier is formed between the metal and a semiconductor called a "Schottky Barrier".

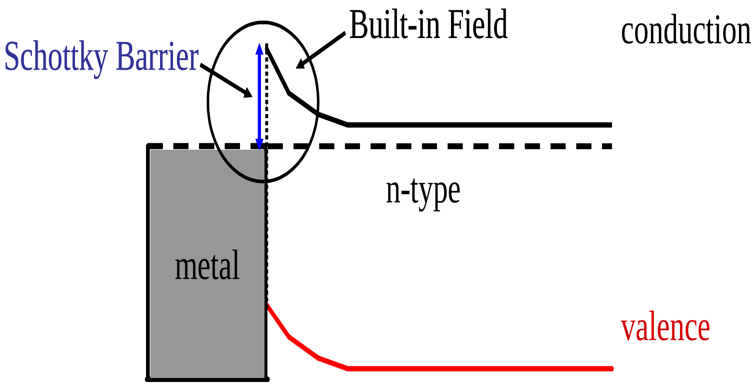
1 Schottky Barrier

When a metal and semiconductor come into contact, equilibrium is established by equalizing the Fermi energies in both materials. Individually, the metal Fermi energy is in the gap of the n-type semiconductor, and the n-type semiconductor Fermi energy is close to the conduction band edge. Therefore, electrons flow from the semiconductor to the metal where they accumulate at the interface.

This sets up a negative surface charge $-\sigma$ and leaves behind a region of positive charge σ which is distributed over a volume of characteristic depth d such that $\rho d = \sigma$, where ρ is the charge density in this so-called *depletion region.*

The total electric field from these charges within the semiconductor at a distance x from the interface is due to three terms: the negative surface charge, the positive volume charge close to the interface, and the positive volume charge toward the semiconductor bulk:

$$E(x) = -\frac{\sigma}{2\epsilon} + \frac{\rho x}{} - \frac{\rho(d-x)}{} = -\frac{\sigma}{} + \frac{\rho x}{} \tag{1}$$



This corresponds to a potential energy

$$U = (-e)V(x) = (-e)(-\int_0^x E(x')dx') = e(\frac{\rho x^2}{2\epsilon} - \frac{\sigma}{\epsilon}x) + C \tag{2}$$

We can set C such that $U(d) = 0$:

$$U = e(\frac{\rho x^2}{2\epsilon} - \frac{\sigma}{\epsilon}x + \frac{\sigma d}{2}) \tag{3}$$

which can be simply written as

$$U = e\frac{\sigma}{2d}(x-d)^2 \tag{4}$$

The band diagram therefore has a quadratic upturn within the depletion region. This corresponds to an electric field (the “built-in field”) which serves to attract the electrons into the bulk once they cross the metal-semiconductor interface. The offset at the interface is called a Schottky barrier. This band diagram asymmetry results in the familiar “rectifying” nature of the Schottky diode, where electron current can flow from the semiconductor into the metal, but not the other way around. This feature is useful when using the Schottky barrier to collect hot electrons, because it serves to keep thermalized electrons from the metal Fermi sea out of the semiconductor.

Here, σ (the amount of charge that collects at the metal-semiconductor interface per contact area) is determined by the Fermi-energy to conduction band offset, and d, the depletion width, is determined by the doping level, since $\sigma = N_d d$. Higher doping levels result in shorter depletion widths to the point where at the degenerate regime, the width is is so short that the Schottky barrier is essentially transparent to tunneling electrons.

2 Spin-Valve Transistor

In keeping with our optical analogy, if one FM film can be used to spin polarize a hot electron current, then two can be used to perform a polarize-analyze experiment, just as we can do with two sheets of Polaroid. When using a tunnel junction (or a forward-biased Schottky, as in the original SVT) to provide hot electrons, this forms the so-called “Spin Valve Transistor”. Measuring the amount of current flowing from the semiconductor to ground while independently changing the FM magnetization of a multilayer film will reveal the magnetocurrent (MC) of the device. (We use the term magnetocurrent because, while there is certainly a current flowing, no external voltage bias is applied because we measure a hot electorn current.)

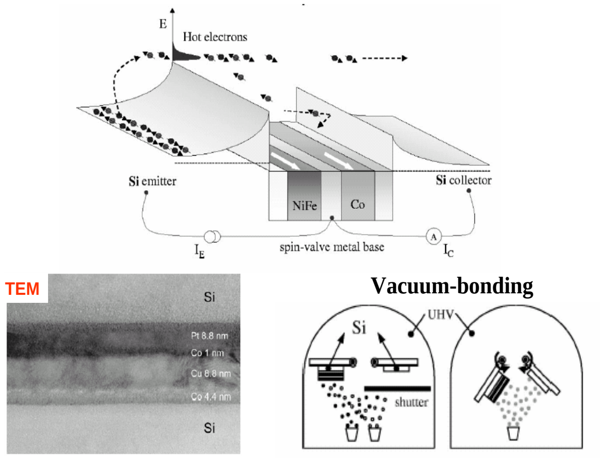


Figure 1: Vacuum bonding is used to make semiconductor-metal-semiconductor devices like the original SVT

In the parallel magnetization configuration, the current carried by the spin-up channel is

$$e^{-w/\lambda^{HI}} e^{-w/\lambda^{HI}} \tag{5}$$

and the spin-down channel is

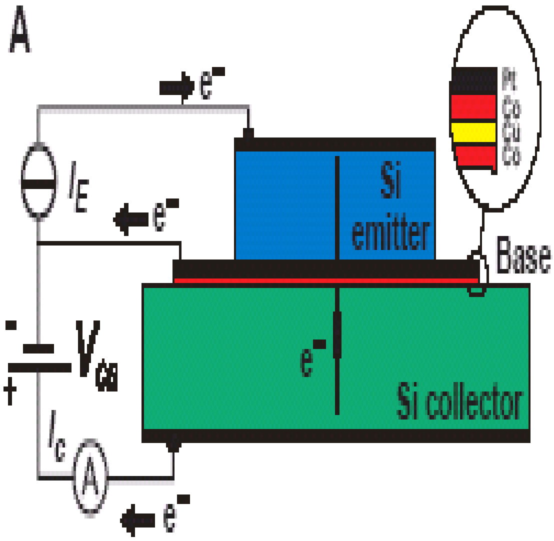


Figure 2: The original SVT used a forward-biased Schottky. The hot electron current is always measured from the collector to ground.

$$e^{-w/\lambda^{LO}} e^{-w/\lambda^{LO}} \tag{6}$$

In the antiparallel magnetization configuration, the current carried by the spin-up channel is

$$e^{-w/\lambda^{HI}} e^{-w/\lambda^{LO}} \tag{7}$$

and the spin-down channel is

$$e^{-w/\lambda^{LO}} e^{-w/\lambda^{HI}} \tag{8}$$

Therefore, the collector current change is given by

$$MC = \frac{e^{-w/\lambda^{HI}} e^{-w/\lambda^{HI}} + e^{-w/\lambda^{LO}} e^{-w/\lambda^{LO}} - (e^{-w/\lambda^{LO}} e^{-w/\lambda^{HI}} + e^{-w/\lambda^{LO}} e^{-w/\lambda^{HI}})}{e^{-w/\lambda^{LO}} e^{-w/\lambda^{HI}} + e^{-w/\lambda^{LO}} e^{-w/\lambda^{HI}}} \tag{9}$$

Now collect terms

$$MC = \frac{e^{-2w/\lambda^{HI}} + e^{-2w/\lambda^{LO}} - 2e^{-w(\frac{1}{\lambda^{LO}} + \frac{1}{\lambda^{HI}})}}{2e^{-w(\frac{1}{\lambda^{LO}} + \frac{1}{\lambda^{HI}})}} \tag{10}$$

$$MC = \frac{e^{-2w/\lambda^{HI}} + e^{-2w/\lambda^{LO}}}{2e^{-w(\frac{1}{\lambda^{LO}} + \frac{1}{\lambda^{HI}})}} - 1 \tag{11}$$

$$MC = \frac{(e^{-2w/\lambda^{HI}} + e^{-2w/\lambda^{LO}})e^{w(\frac{1}{\lambda^{LO}} + \frac{1}{\lambda^{HI}})}}{2} - 1 \tag{12}$$

$$MC = \frac{e^{w(\frac{1}{\lambda^{HI}} - \frac{1}{\lambda^{LO}})} + e^{-w(\frac{1}{\lambda^{HI}} + \frac{1}{\lambda^{LO}})}}{2} - 1 \tag{13}$$

$$MC = \cosh w(\frac{1}{\lambda^{HI}} - \frac{1}{\lambda^{LO}}) - 1 \tag{14}$$

$$MC = \cosh \frac{w}{\lambda^{HI}}(1 - \frac{\lambda^{HI}}{\lambda^{LO}}) - 1 \tag{15}$$

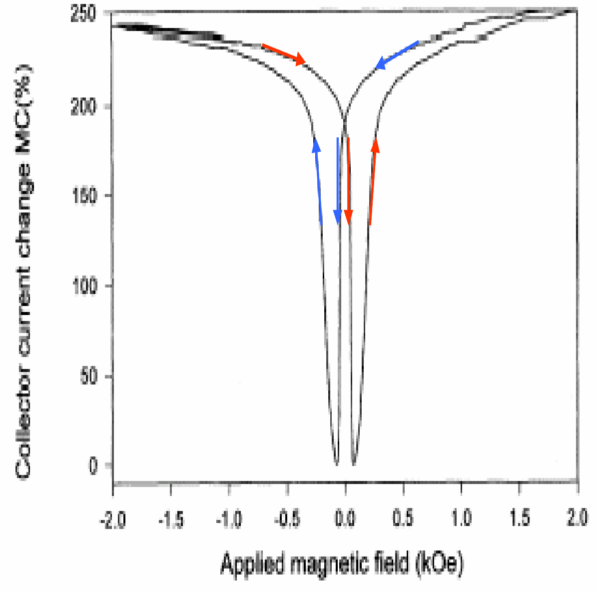
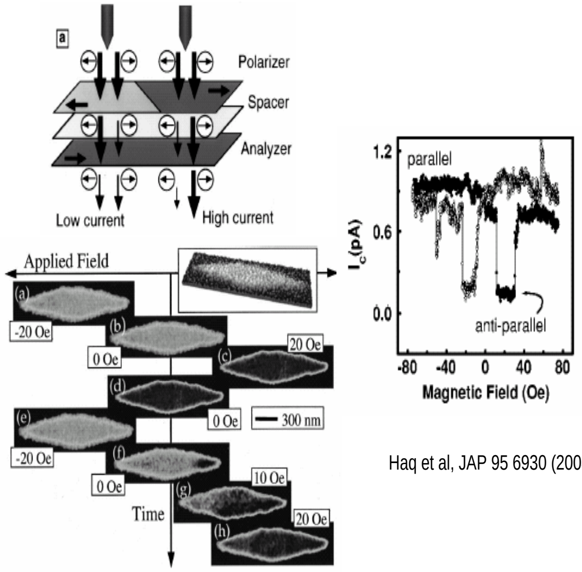


Figure 3: Spin valve transistor hysteresis

This expression grows exponentially with $\frac{\lambda^{HI}}{\lambda^{LO}}$, unlike GMR which nominally behaves like

$$GMR\% = \frac{(1-\frac{\lambda^{HI}}{\lambda^{LO}})^2}{4\frac{\lambda^{HI}}{\lambda^{LO}}} \tag{16}$$



Haq et al, JAP 95 6930 (2004)

Rippard and Buhrman, APL 75 1001 (1999); APL 77 1357 (2000)

Figure 4: Hot electron injection with a STM allows spatial maps of magnetization in microstructures

As previously mentioned, there are other options to provide hot electrons. The original device used a forward biased Schottky in a vacuum-bonded SMS structure, and there have been several studies of spatially-resolved MC using the tunneling tip from a STM. Our analysis here supposed that the two FM layers were in the metal base, but we could also put one metal in the emitter, making a so-called "Magnetic Tunnel Transistor". At Harvard, I proposed using hot electrons scattered by sub-bandgap photons via internal photoemission, which enables two-

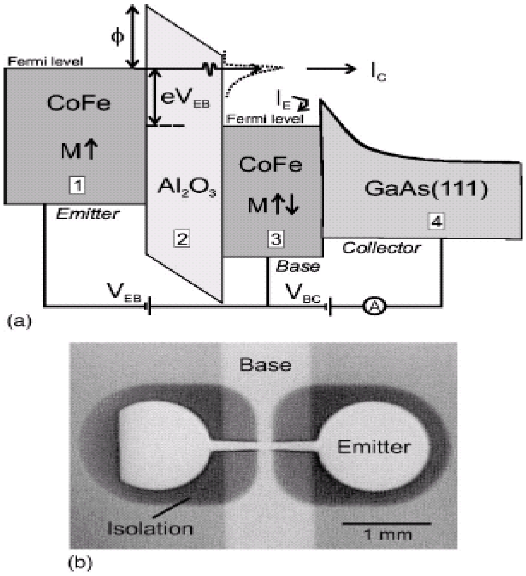


Figure 5: Magnetic Tunnel Transistor

terminal operation in a device I called the "Spin-Valve Photodiode". Here we present the reasoning behind the original theoretical model put forth.

3 Spin-valve Photodiode

In this device, we replace the three-terminal injection of hot electrons with photo-excitation using sub-bandgap photons. This process is called Internal Photo-Emission (IPE). The photocurrent caused by IPE can be modeled by integrating the contributions from all depths within the metal contact of thickness d, accounting for photon attenuation (with skin depth σ) from the surface and hot electron attenuation (with mean free path λ) to the metal-semiconductor interface.

$$I \propto \int_0^d e^{-\frac{x}{\sigma}} e^{-(\frac{d-x}{\lambda})} dx \tag{17}$$

$$I \propto e^{-\frac{d}{x}} \int_0^d e^{x(\frac{1}{\lambda}-\frac{1}{\sigma})} dx \tag{18}$$

$$I \propto e^{-\frac{d}{x}} \frac{e^{x(\frac{1}{\lambda}-\frac{1}{\sigma})}}{\frac{1}{\lambda}-\frac{1}{\sigma}} \Big|_0^d \tag{19}$$

$$I \propto e^{-\frac{d}{x}} \left[\frac{e^{d(\frac{1}{\lambda}-\frac{1}{\sigma})} - 1}{\frac{1}{\lambda}-\frac{1}{\sigma}} \right] \tag{20}$$

$$I \propto \frac{e^{-\frac{d}{\lambda}} - \frac{d}{\sigma}}{\frac{1}{\lambda}-\frac{1}{\sigma}} = \frac{\lambda\sigma}{\sigma-\lambda} \left[e^{-\frac{d}{\lambda}} - e^{-\frac{d}{\sigma}} \right] \tag{21}$$

In a magnetic multilayer, we need to determine the current from each spin component in each film since the σ's and λ's are different for each metal.

$$I_0 \sum_i \left[\prod_{j>i} \exp\left(-d^j/\sigma^j\right) \right] \frac{\sigma^i \lambda_\uparrow^i}{\sigma^i - \lambda_\uparrow^i} \left(\exp(-d^i/\sigma^i) - \exp(-d^i/\lambda_\uparrow^i) \right) \prod_{j<i} \exp\left(-d^j/\lambda_\uparrow^j\right) \tag{22}$$

Despite the obvious simplicity of this model, recent experimental work in my lab has indicated that modifications are necessary to explain observed MC dependence on the film thicknesses (see upcoming article in *JAP*).

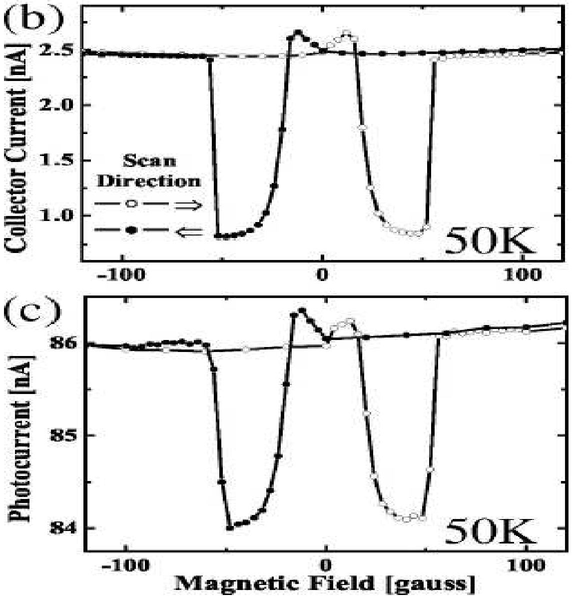


Figure 6: (top) SVT operation with TJ at -1.5V (bottom) SVPD operation with 1310nm photons