

Single Crystal Tunnel Junctions

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We have grown single crystal epitaxial Magneto Tunneling Junctions using Fe whisker substrates, MgO(001) oxide spacers and Fe/Ni/Au(001) top electrodes. Fe whiskers crystals were prepared by chemical vapor transport. The Fe whiskers are long square bars, 100-300 μm wide and 5-10mm long, with their facets oriented in {001} crystallographic directions. Their facets are nearly perfect atomic planes with the terrace size of several microns. MgO layers were deposited by an electron beam evaporator using a pure bulk MgO target. Reflection High Energy Electron Diffraction (RHEED) and Low Energy Electron Diffraction (LEED) patterns showed that MgO films are crystalline with Fe[100] parallel to MgO[110]. The MgO layers grow pseudomorphically up to 7 ML. In the unrelaxed state that results in 3.5% compression of MgO. The growth shows well defined RHEED oscillations and the RHEED diffraction spots are similar to those of Fe whiskers indicating that the growth of MgO proceeds in layer by layer growth. After deposition of 7ML the LEED and RHEED diffraction features show a sharp onset of misfit dislocations in MgO. The tunneling studies were carried out before the onset of misfit dislocations. The tunneling barrier of 3.6eV was determined by UPS using the MgO Oxygen 2p valence band gap edge and the Fermi surface of Fe assuming that the band gap in MgO is 7.8eV. Samples were prepared by MBE with the growth rate of $\sim 1\text{ML}/\text{min}$. After preparation, samples were transferred into OMICRON AFM/STM system. They were degassed for 24 hours. In order to achieve reproducible tunneling characteristics the conducting tip and the sample was covered by additional 4ML thick Au in situ by MBE. During the measurement the conducting tip was in contact mode touching the upper Fe/Ni/Au(001) electrode. The I-V characteristics were measured between -2 to +2 V. A fit to the measured I-V curve using Simmons rule resulted in the MgO spacer of $10.2 \pm 1.8 \text{ \AA}$ and the tunneling barrier of $3.7 \pm 0.1 \text{ eV}$ in very good agreement with the oxide film thickness of 10.5 $\text{\AA}$ measured by the RHEED intensity oscillations and the barrier height determined by UPS. The grown MgO layer is of very good quality. One needs to apply 10 V to reach the electrical break down in 10 $\text{\AA}$ thick MgO layer. No pinholes were observed prior to high applied voltage. The spatial properties of the tunnel junction were imaged by scanning the AFM tip in contact mode. We were able to observe the rows of (5x1) surface reconstruction of Au(001) and the atomic steps with the resolution of 2 nm indicating that the contact area is close to $2 \times 2 \text{ nm}^2$. Most of the scanned areas show low tunneling currents of the order of fraction of nA

at 2V as expected for the MgO tunneling barrier. However there are spikes in current up to several nA in strength. The width of spikes varies from 10nm down to the contact resolution of a few nm. The position of spikes showed no obvious correlation to the surface topography indicating that sharp increases in tunneling current were caused by localized defects in the MgO layer. The tunneling current recovers its low value once the tip is moved away from the spike. The fact that one is able to see the individual spikes in tunneling current is a nontrivial result and perhaps the most important result of this work. The AFM tip touches the upper conducting electrode, the sheet resistance of metallic upper electrode is by many orders of magnitude smaller than that of the MgO layer. In the limit of a simple electric continuum, the upper electrode should reach the potential level of the tunneling tip and consequently the lateral contrast on nanoscopic scale should be absent. The observed high lateral resolution is consistent only with ballistic electron transport. The electrons are emitted from the tip in nearly perpendicular direction to the film surface, and traverse the upper metallic electrode without scattering. That implies that the component of k-vector parallel to the sample surface is not appreciably changed, tunneling is coherent. The realization of ballistic tunneling in our system is possible because the mean free path of electrons in crystalline upper metallic electrode is much bigger than the film thickness and the lateral dimensions of the contact area. We have studied the nature of the current spikes using I-V characteristics. The I-V characteristics in spikes are very asymmetric and the tunneling barrier is significantly decreased. Such an asymmetric shape can't be explained by thinner barrier. The significant decrease in the tunneling barrier indicates the presence of dopants in the MgO band gap, and the highly asymmetric I-V characteristics show that the distribution of dopants is asymmetric around the metal/oxide interfaces.

In conclusion: We have shown that we have grown highly perfect crystalline epitaxial MTJ structures using MgO dielectric layers. We have demonstrated that a conducting tip of AFM system can be used to study ballistic tunneling allowing one to investigate local tunneling characteristics with the lateral resolution of $2 \times 2 \text{ nm}^2$. A small fraction of the scanned area showed defects in MgO layers, however the spikes do not dominate the total tunneling current.

0-7803-5943-7 4/00/\$10.00 ©2000 IEEE.

DA-06