Fabrication and Characterization of MgO-Fe-MgO Granular Films

N. Pai, M. Kudo, K. Wakasugi, M. Arita, and Y. Takahashi
Graduate School of Information Science and Technology, Hokkaido University, Sapporo, Japan

Single electron tunneling (SET) transistors utilize conductive islands sandwiched by two electrodes via tunnel barrier around 1 nm thick to control tunneling of single electrons. Unlike typical field-effect transistors, these devices operate with quantized levels of charge and not thousands of electrons. Such transistors have the potential for higher capacity and more power-efficient devices ranging from quantum computers to magnetoresistance random access memory. In order to better implement these transistors, usage of SET ferromagnetic materials should be combined with tunnel magnetoresistance to enhance effects by gate voltage. The present work explores the effect of substrate deposition temperature and insulating barrier thickness of MgO-Fe-MgO granular-type devices on the tunneling effect where one ferromagnetic layer of nanoparticles is deposited between electrodes. Samples of 1.5 nm thick Fe granula, or dots, in between two 2 nm thick MgO films were created using molecular beam epitaxy (MBE) at various substrate temperatures of 23 (room temperature), 100, 120, and 140°C. Au/Cr electrodes were then deposited on them using vacuum deposition. Results from magnetoresistance, temperature-resistance, current-voltage measurements at room temperature (293 K) and a conventional low temperature (4.5 K), and transmission electron microscopy (TEM) images indicated metallic conduction for RT and tunneling conduction for 120 C. The sample prepared at 100 C exhibited primarily tunneling characteristics but with a weak indication of anisotropic magnetoresistance which is characteristic of metallic conduction. The sample at 140 C was expected to show clear tunneling conduction; however, it showed metallic characteristics. In conclusion of the present work, to realize tunneling conduction of MgO-Fe (1.5 nm thick)-MgO, film deposition should be performed well above 100 C. The main area of further interest is reducing the size of the macroscopic film sheets to suit miniaturized devices, which reduces the number of Fe particles necessary for clear observation of SET effects in and out of the magnetic field.

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Purpose

- Realization of spin-dependent single electron tunneling (SET) transistors
- Investigate deposition conditions to obtain nano-island Fe films on MgO
  - -Substrate deposition temperature
  - -Fe film thickness

Background

Tunneling magnetoresistance (TMR) is a result of spin-dependent tunneling where there is an imbalance of up- and down-spin electrons tunneling from one ferromagnet to another through a tunneling barrier.

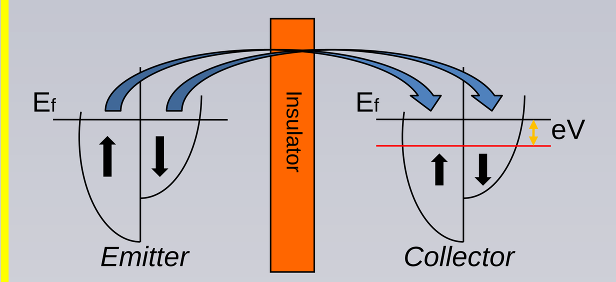


Fig. 1a – Electron tunneling between two FM materials in parallel configuration.

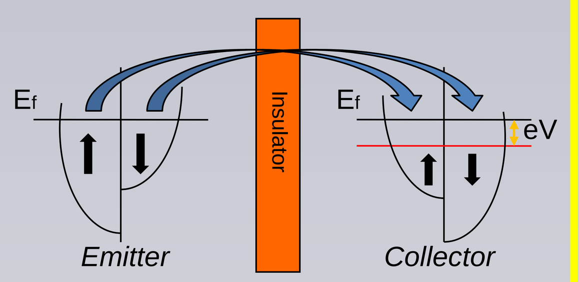
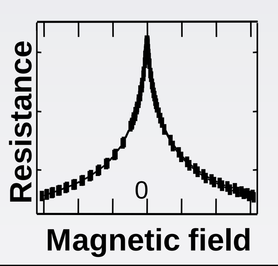
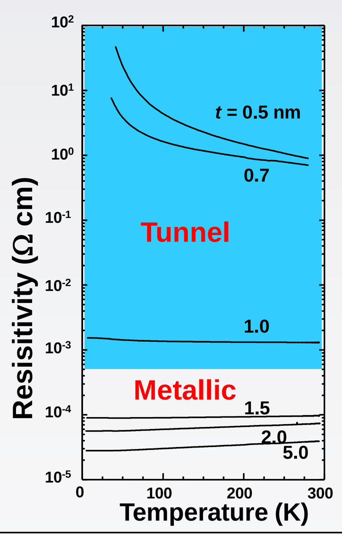
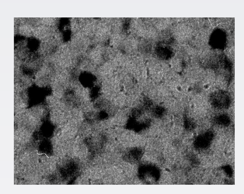
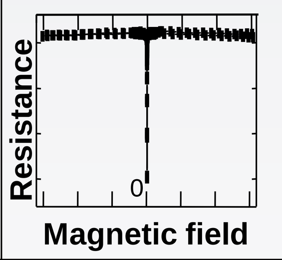
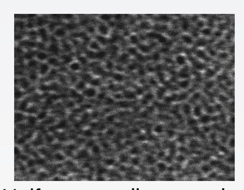


Fig. 1b – SET in antiparallel (high resistance) configuration

SET occurs when a thin tunnel barrier, like 1 nm thick MgO, containing conductive nanodots, is sandwiched between two electrodes. Only quantized charges can pass from the emitter to collector due to the specific allowed states.

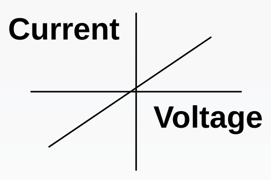
In order to increase effects of gate voltage using TMR, SET ferromagnetic materials should be placed in the tunnel barrier and observed.

The samples will exhibit either tunneling or metallic conduction through characteristics shown below:

Conduction type	MR-curve	ρT-curve	TEM image
Tunnel			 Black dots are Fe granular amidst MgO
Metallic			 Uniform, smaller granular compared to tunneling

IV-curve

Expected to be linear for both conduction types in the case of large-size samples



Applications

Magnetoresistive Random Access Memory (MRAM)
- •Nonvolatile memory
- •Higher capacity
- •Low power consumption

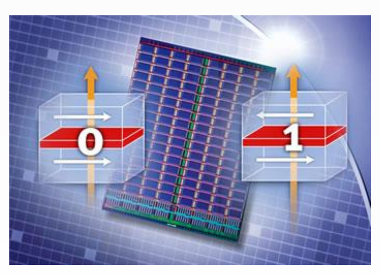


Fig. 2 – Artistic representation of memory cell array and 0- (parallel) and 1-bit (antiparallel) orientations

http://www.lbl.gov/Science-Articles/Archive/sabl/2005/March/assets/MRAM.jpg

Method

Molecular Beam Epitaxy (MBE)

Solid source materials (i.e., MgO & Fe) hit by electron guns are evaporated in an ultra-high vacuum and deposited onto heated substrate being rotated for homogenous growth.

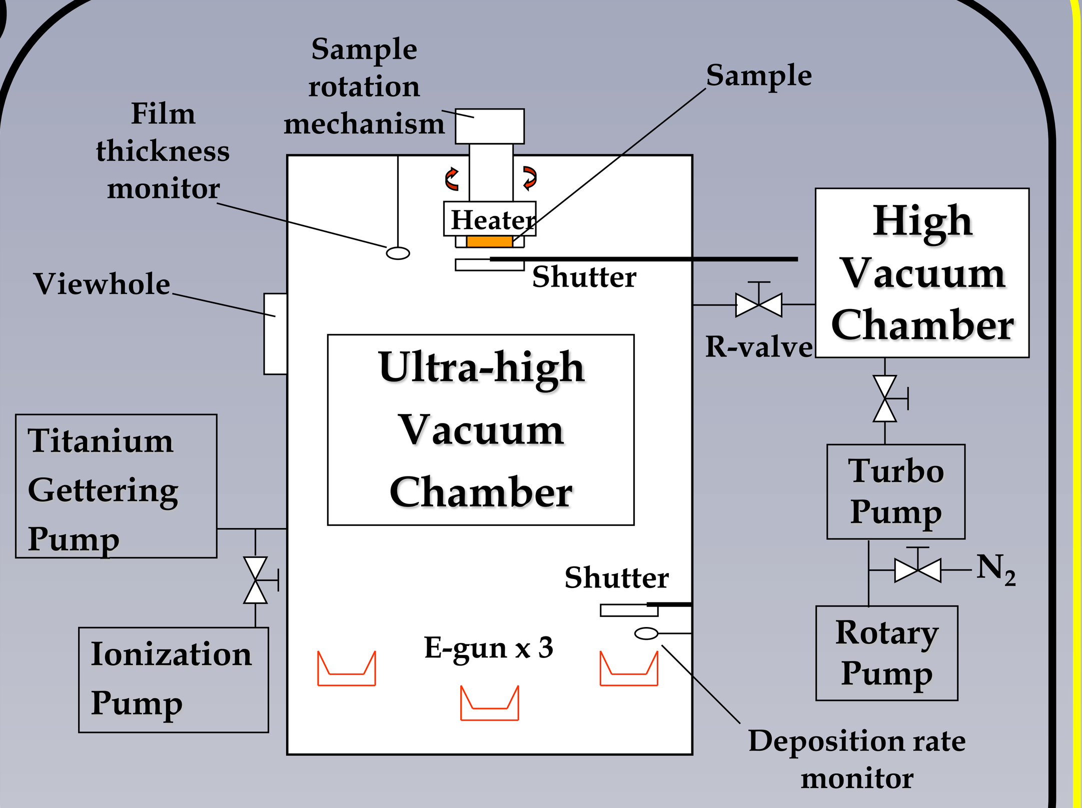


Fig. 3 – Diagram of MBE system

Ultra-high vacuum is ~10^{-11} Torr; high vacuum is ~10^{-9} Torr

Vacuum Deposition System

Place masked granular films into system, then deposit electrodes as follows:
- •Cr (~6 nm) – Buffer layer between conducting Au and MgO-Fe-MgO
- •Au (~100 nm) – Contact with indium wires connected to gate terminals

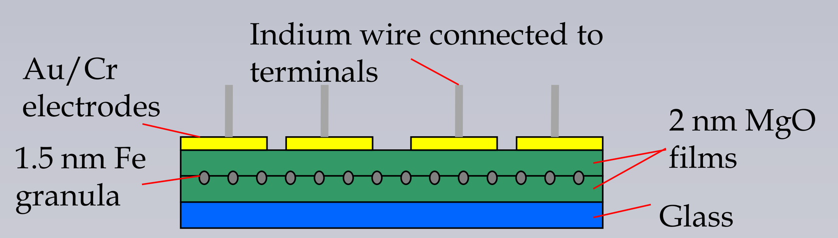


Fig. 4 - Cross-section of a sample

Resistance Measurement System

- •Magnetoresistance (MR curve)
  ±15 kOe, room temperature (RT) & 4.5 K
- •Resistivity-Temperature curve (ρT curve)
  (4.5 K – RT, 0 Oe)
- •Current-Voltage (IV curve)
  (RT & 4.5 K)

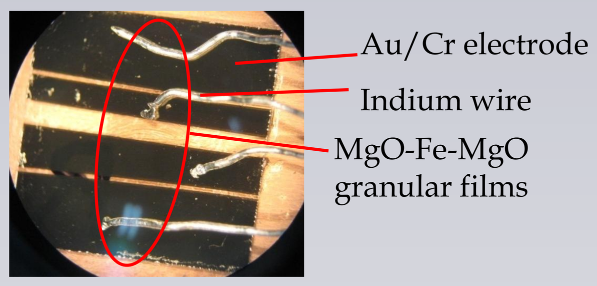


Fig. 5 - Electrodes and indium wires under a microscope.

Transmission Electron Microscopy (TEM)

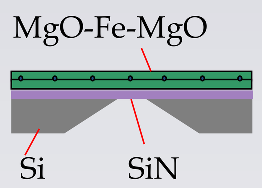
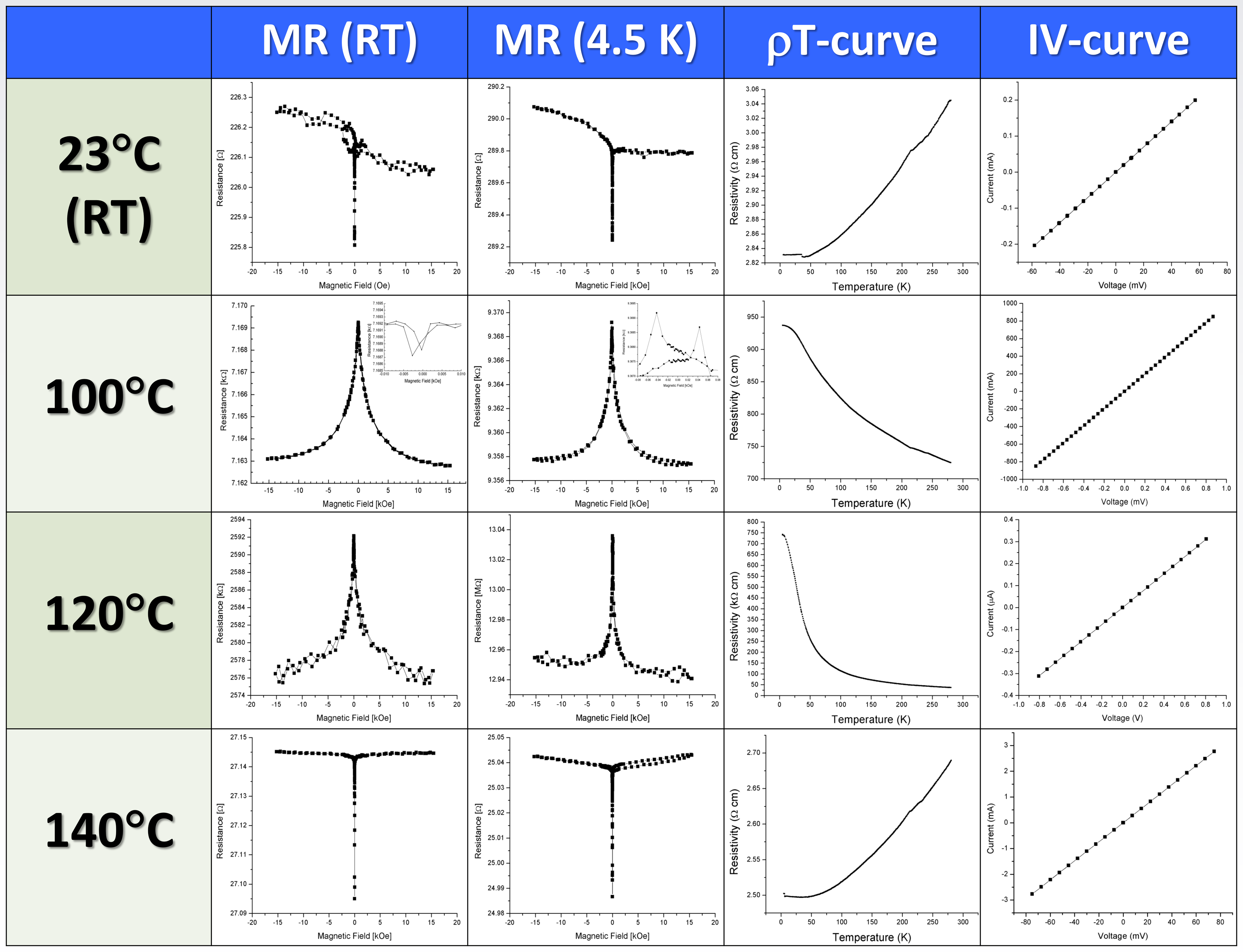


Fig. 6 – Diagram of thin film (~10 nm) SiN sample used for TEM analysis.

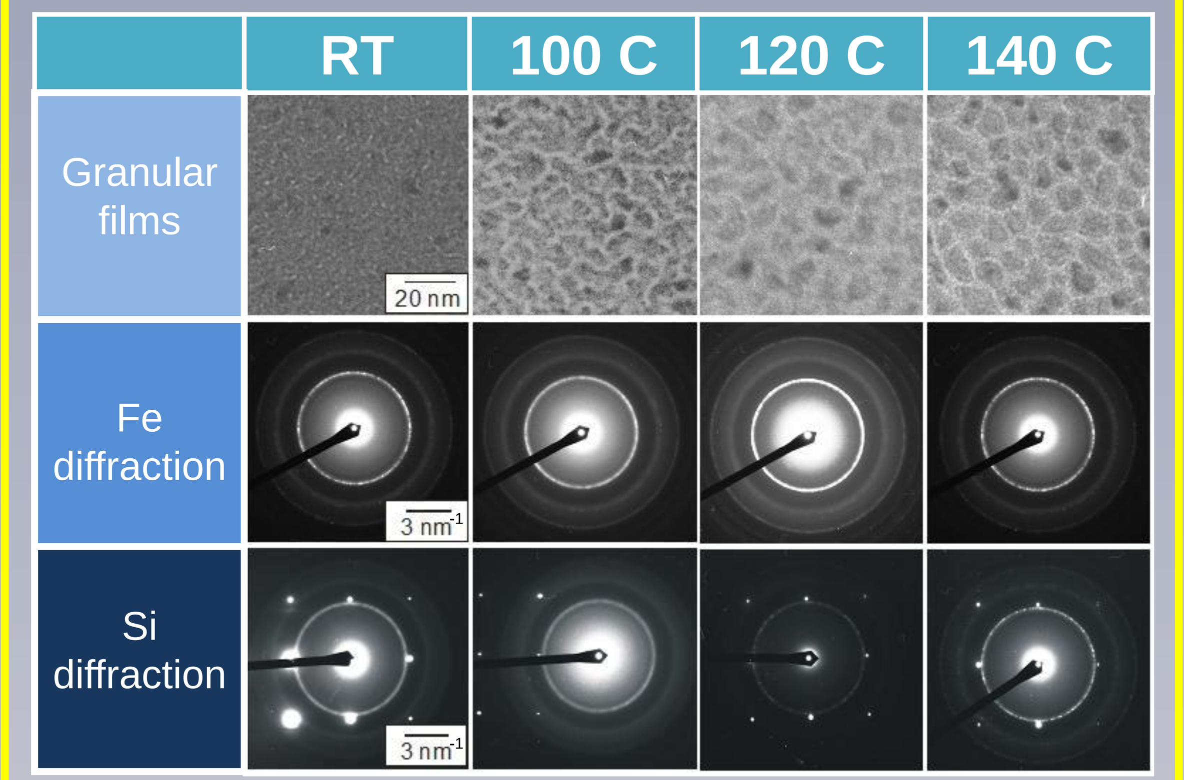
Fig. 7 – Picture of a TEM machine

http://www.nims.go.jp/analysis/TEM.jpg

Data



TEM Images



The TEM image of the RT sample shows small Fe particles interspersed with MgO. The 100°C sample exhibits connected pairs. 120°C sample shows greater separation and larger particles, and the 140°C sample has distinctly individual particles.

*Fe and Si diffraction patterns are used to determine Fe lattice parameter and particle sizes.

Results

T_s (°C)	RT	60	80	100	120	140	200
t=0.5 nm	T						
0.7	T			T			
1.0	T	T	M	M	T		T
1.5	M			T/M	T	M	
2.0	M						

(T = tunneling conduction, M = metallic conduction)

*100°C sample primarily exhibited tunneling conduction characteristics, but close inspection of its MR-curve near 0 Oe revealed metallic conduction characteristic.

Conclusion

Due to the transition from metallic to tunneling conduction from RT to 120°C, 140°C was expected to exhibit strong tunneling. However, it exhibited strong metallic conduction, and its electrical properties did not correspond to characteristics suggested by the TEM image.

The results of the present work suggest that for tunneling conduction in MgO-Fe(1.5 nm thick)-MgO film depositions should be conducted well above 100°C.

The main objective for further studies is reducing the size of the macroscopic film sheets to suit miniaturized devices. This can be accomplished by reducing the number of Fe particles necessary for clear observation of SET effects in and out of the magnetic field.

NanoJapan
RICE

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