SPICE Model for Magnetic Tunnel Junctions

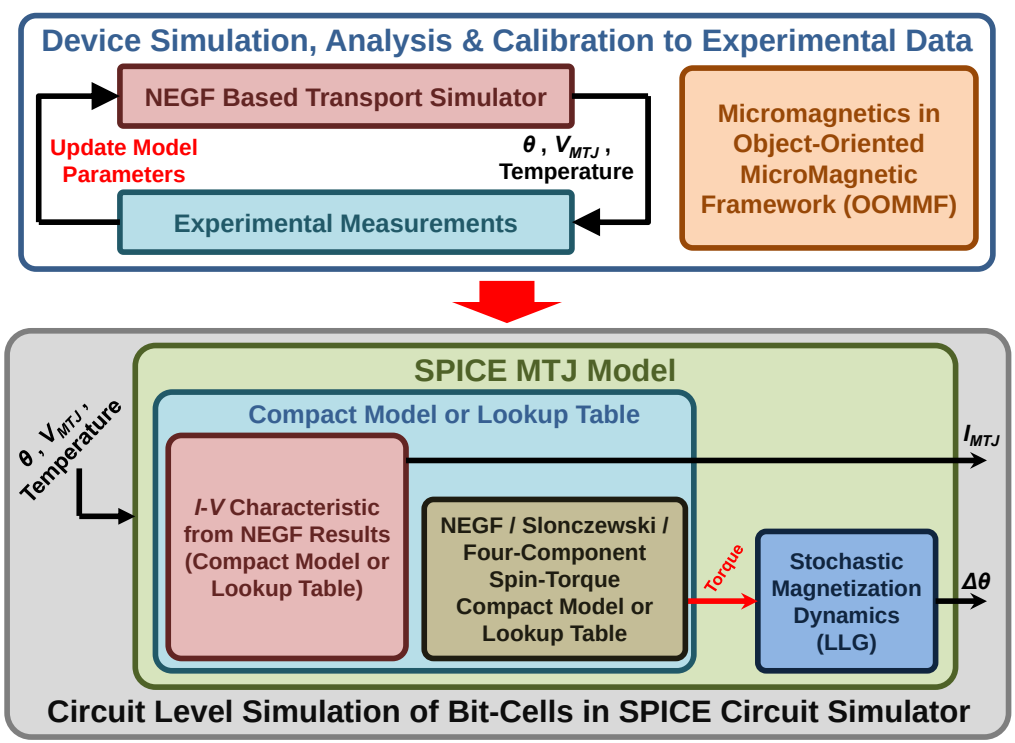
Xuanyao Fong, Sri Harsha Choday, Georgios Panagopoulos
Charles Augustine, and Kaushik Roy

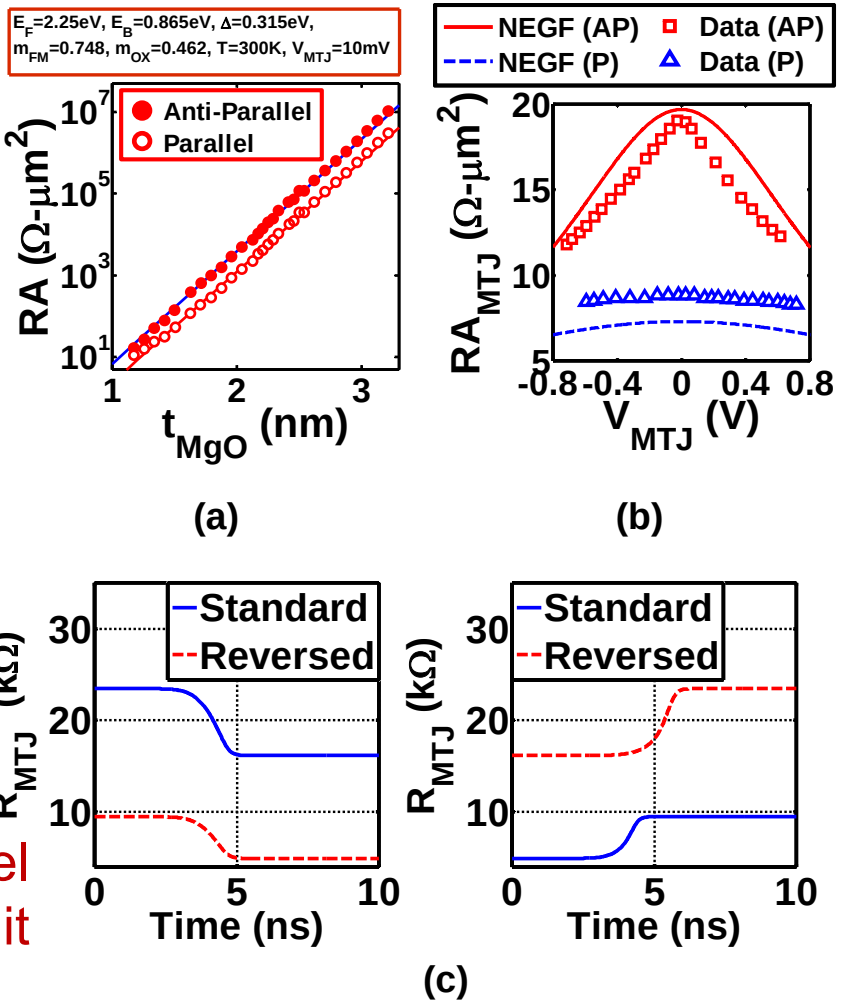
Department of Electrical and Computer Engineering,
Purdue University, West Lafayette, IN
https://engineering.purdue.edu/NRL/index.html

C-SPIN

STARnet

Overview





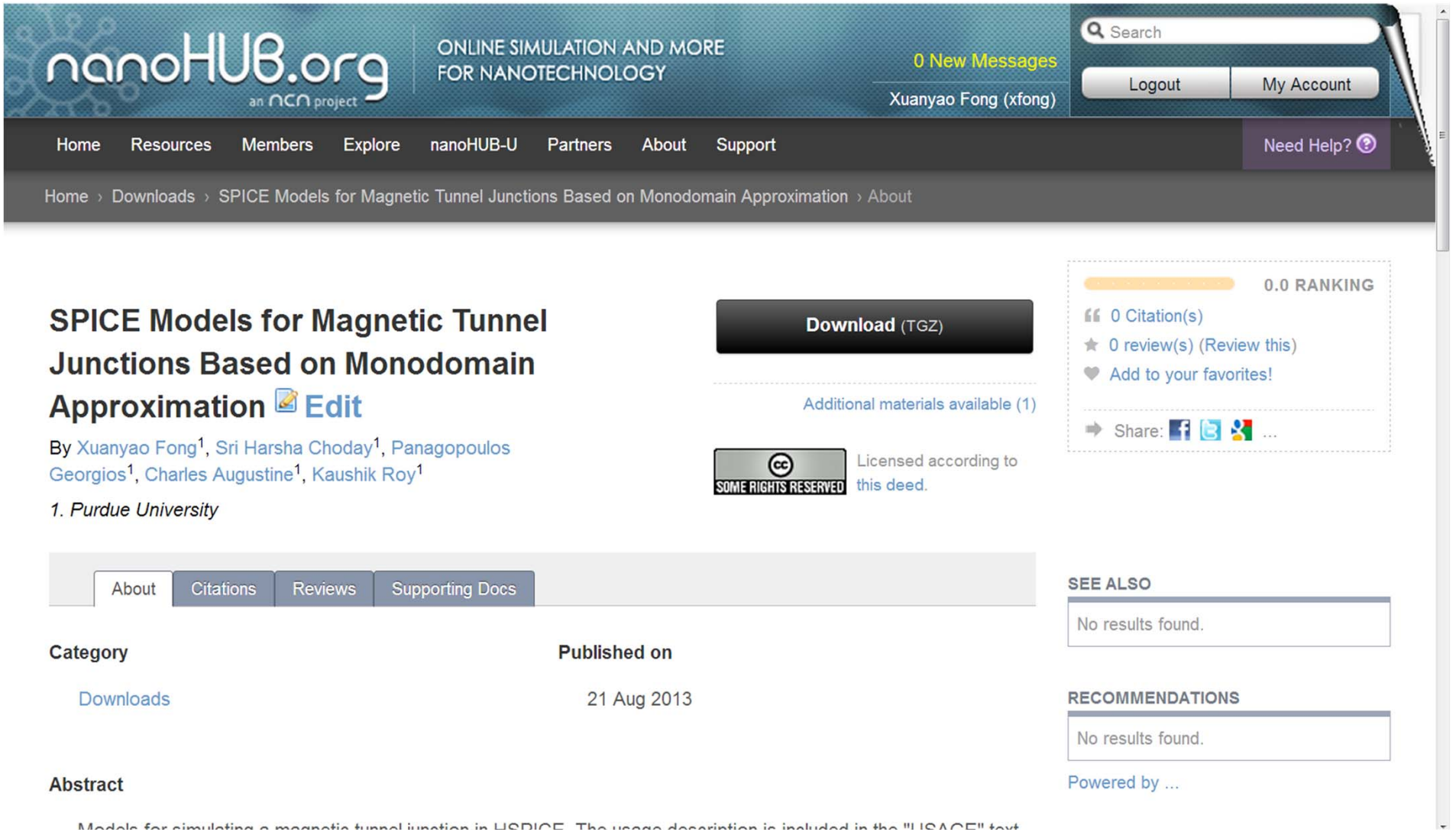
Parameters for calibration of device level simulation go into SPICE model for circuit level simulations.

a) S. Yuasa *et al*., *Nature Materials* vol. 3, no. 12, pp. 868-871, Dec. 2004, b) C. J. Lin *et al.*, *IEDM*, Dec. 2009, pp. 11.6.1-11.6.4, c) T. Kishi *et al.*, *IEDM*, Dec. 2008, pp. 12.6.1-12.6.4.

Where To Get The Files?

NanoHub.org

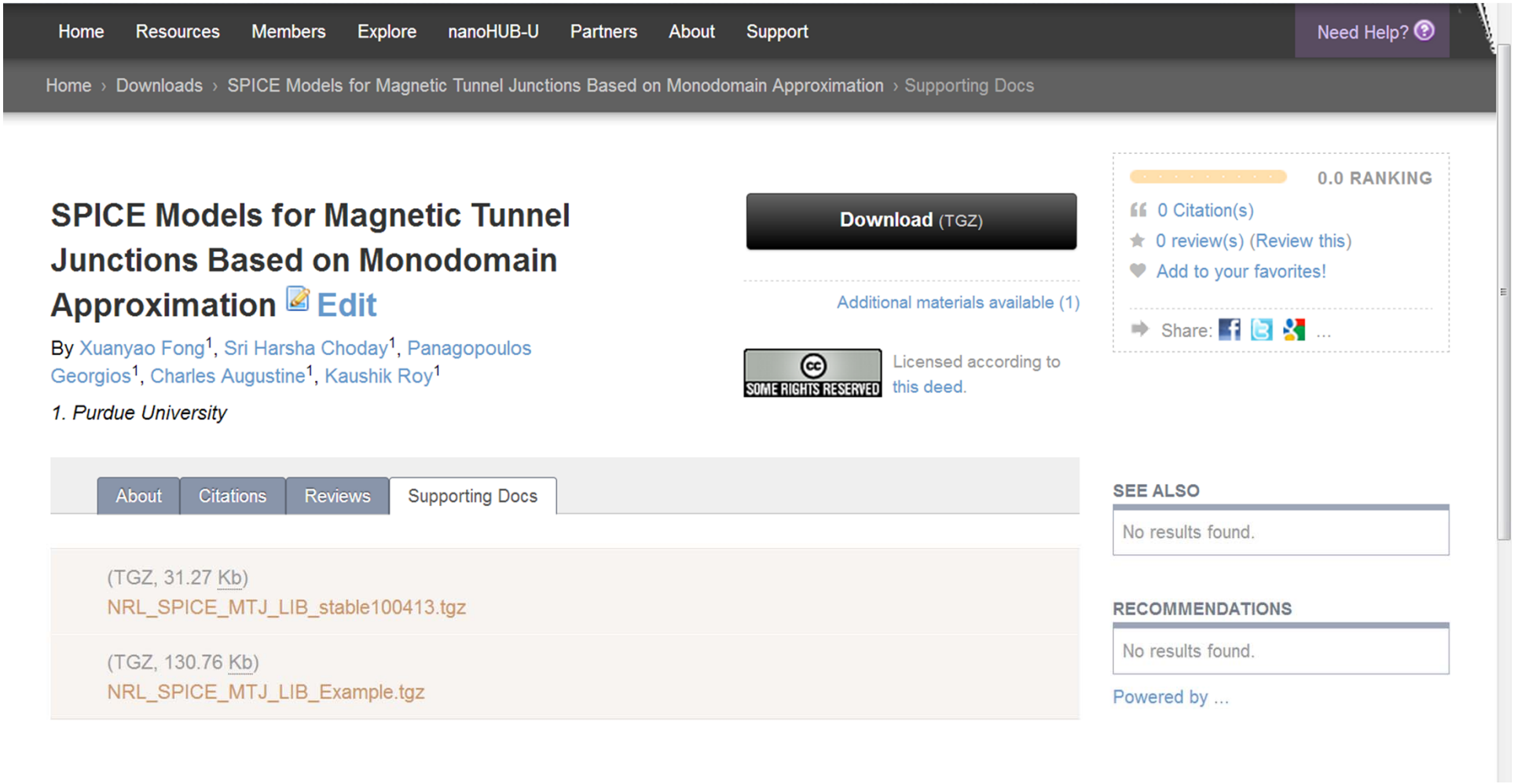
https://nanohub.org/resources/19048



Where To Get The Files?

NanoHub.org

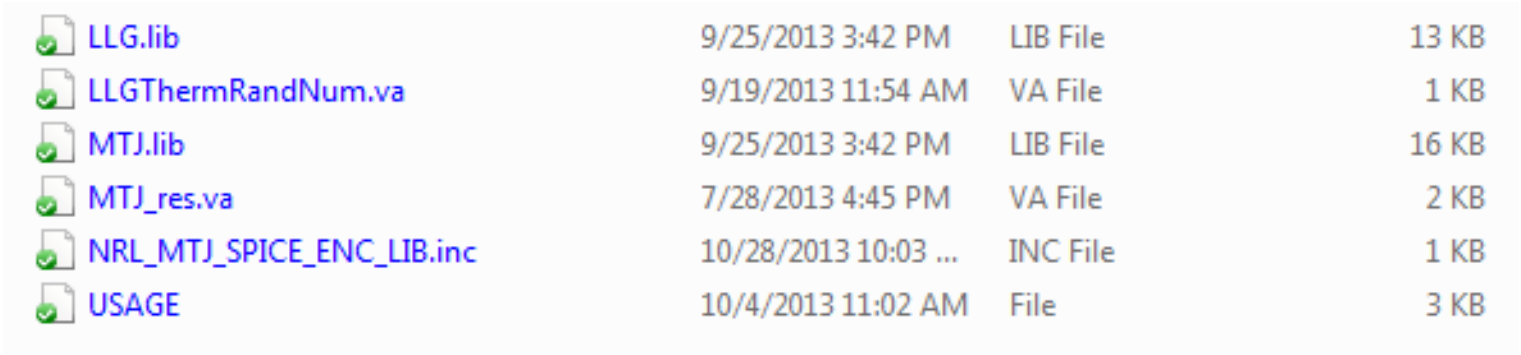
https://nanohub.org/resources/19048



Archive Contents

NRL_SPICE_MTJ_LIB_stable100413.tgz

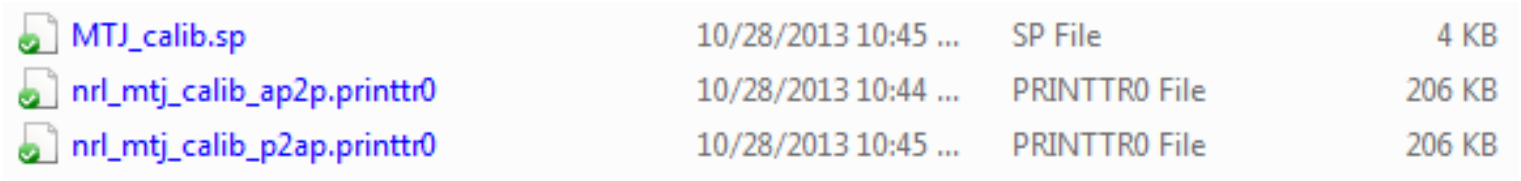
Contains a directory “mtj_libs_encoded”



LLG.lib	9/25/2013 3:42 PM	LIB File	13 KB
LLGThermRandNum.va	9/19/2013 11:54 AM	VA File	1 KB
MTJ.lib	9/25/2013 3:42 PM	LIB File	16 KB
MTJ_res.va	7/28/2013 4:45 PM	VA File	2 KB
NRL_MTJ_SPICE_ENC_LIB.inc	10/28/2013 10:03 ...	INC File	1 KB
USAGE	10/4/2013 11:02 AM	File	3 KB

NRL_SPICE_MTJ_LIB_Example.tgz

Contains a directory “stt”

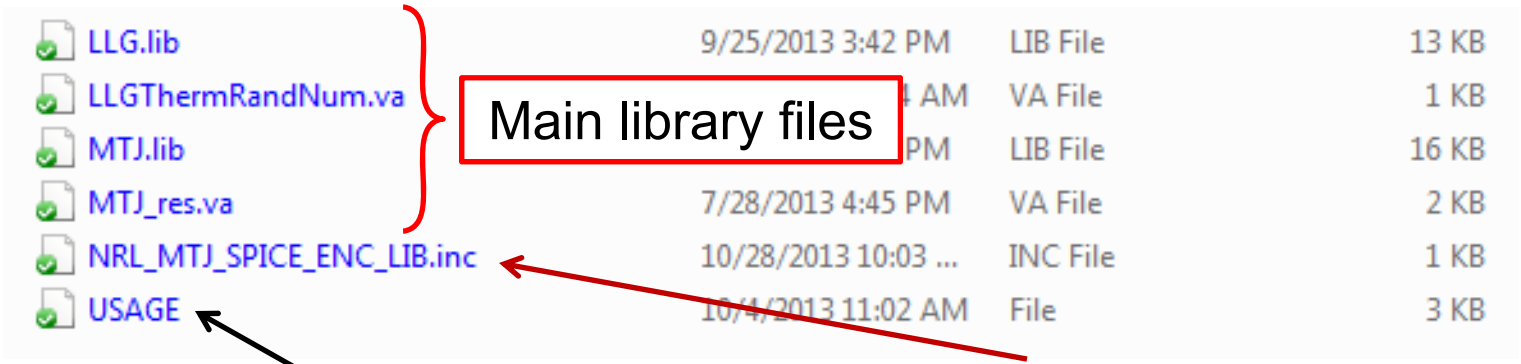


MTJ_calib.sp	10/28/2013 10:45 ...	SP File	4 KB
nrl_mtj_calib_ap2p.printtr0	10/28/2013 10:44 ...	PRINTTR0 File	206 KB
nrl_mtj_calib_p2ap.printtr0	10/28/2013 10:45 ...	PRINTTR0 File	206 KB

Archive Contents

NRL_SPICE_MTJ_LIB_stable100413.tgz

Contains a directory “mtj_libs_encoded”



Readme file: your best resource
Also contains default values, description of model parameters, etc.

Include file for convenience

NRL_SPICE_MTJ_LIB_Example.tgz

Contains a directory “stt”

Example SPICE Netlist

Example Netlist - Header

```
**********************************************************************************
**********************************************************************************
**                                                                              **
**                                MTJ_calib.sp                                  **
**                                                                              **
**********************************************************************************
**********************************************************************************
**********************************************************************************
** Author: Xuanyao Fong
** Email: xfong@ecn.purdue.edu
**********************************************************************************
** This SPICE file demonstrates the operation of an MTJ device.
**********************************************************************************

**********************************************************************************
***                             Libraries                                      ***
**********************************************************************************
.inc './mtj_libs_encoded/NRL_MTJ_SPICE_ENC_LIB.inc'
```

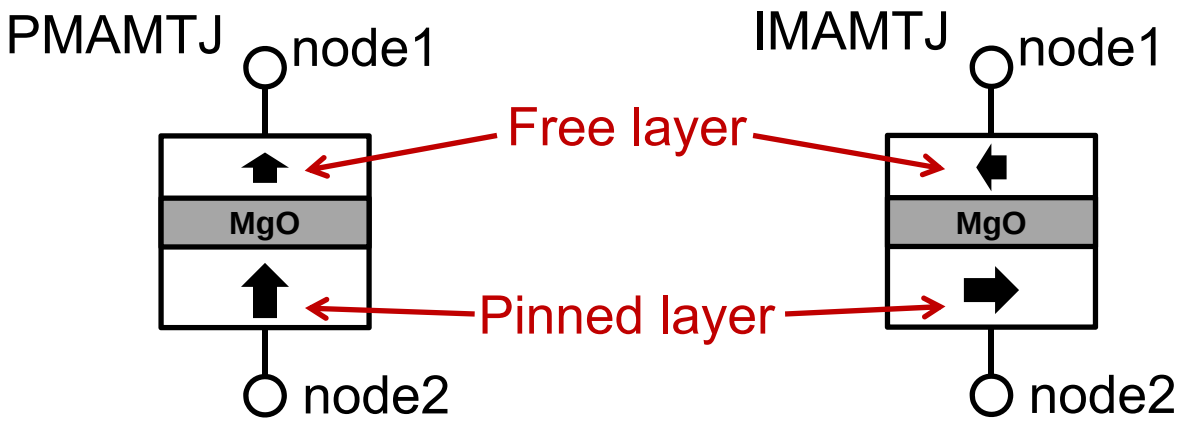
SPICE include file in archive for convenience

SPICE options given in the file were used to correct for accuracies due to different numerical integration method used in SPICE and in OOMMF.

Always ensure simulation results converge!!!

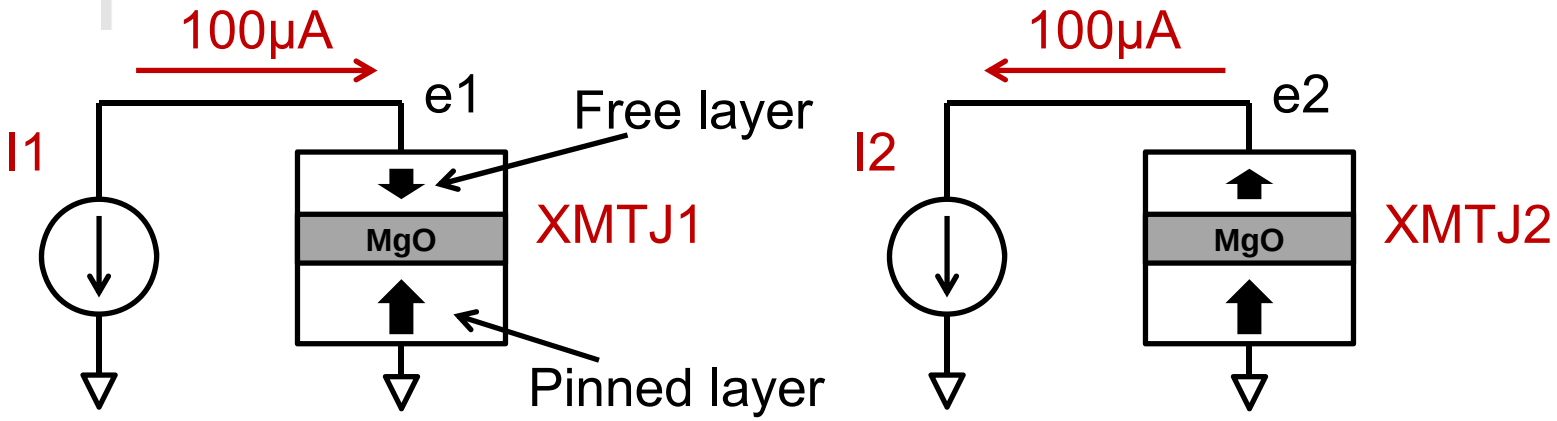
Example Netlist - Instantiation

```
**** Available MTJ models:
1) PMAMTJ
2) IMAMTJ

**** Example line to instantiate the model in your netlist:

X* node1 node2 node3 node4 node5 *MTJ
+ W='width' L='length' Tm='t_FL' TMgO='TMgO'
+ alpha='damping' Ms='Msat' Ku2='Ku2'
+ th_hard='th_hard' phi_hard='phi_hard'
+ LLG_Temp='Temperature' mu_r_therm='mu_r_therm'
+ thermScale='therm_scale'

- node1 is the node name for the free layer of the MTJ

- node2 is the node name for the hard layer of the MTJ

- Voltages of node3, node4, and node5 represent the
  x, y, and z-components of the applied magnetic field
  on the free layer (in CGS units), respectively.
```



Example Netlist - Instantiation

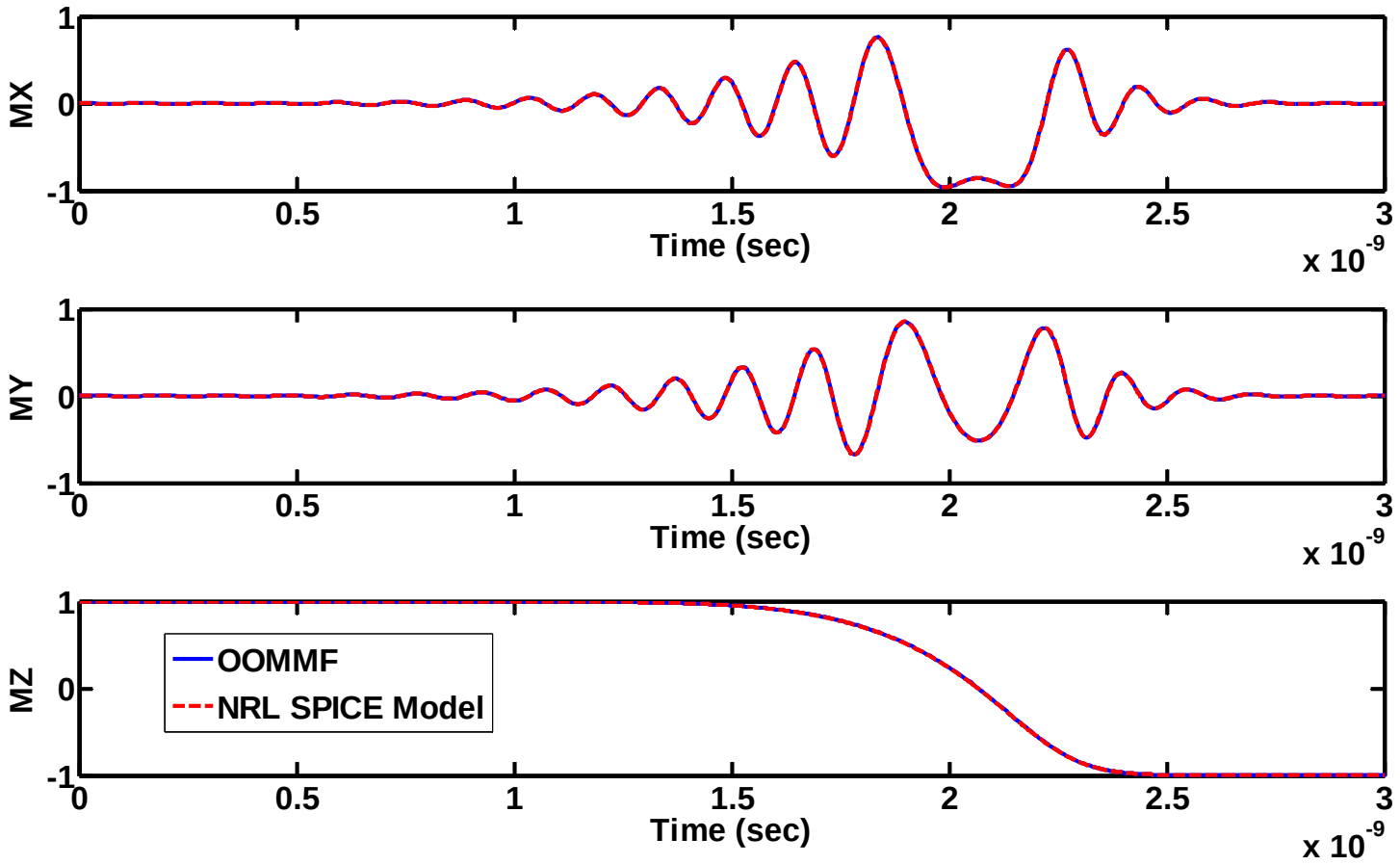
```
V_HAX hax 0 '0.0'
V_HAY hay 0 '0.0'
V_HAZ haz 0 '0.0'

I1 0 e1 '-100e-6'
XMTJ1 e1 0 hax hay haz PMAMTJ Ku2='K' W='W' P_L='P_L' P_R='P_R'
+ L='L' Tm='Tm' Ms='Ms' Lambda=0 alpha='alpha' Lambda_L='Lambda_L'
+ Lambda_R='Lambda_R'

I2 0 e2 '100e-6'
XMTJ2 e2 0 hax hay haz PMAMTJ Ku2='K' W='W' P_L='P_L' P_R='P_R'
+ L='L' Tm='Tm' Ms='Ms' Lambda=0 alpha='alpha' Lambda_L='Lambda_L'
+ Lambda_R='Lambda_R'
```




```
**********************************************************************
***                      Initial Conditions                        ***
**********************************************************************
.ic V(XMTJ1.XLLG_Eq.thInt) '0.1*pi/180'
.ic V(XMTJ1.XLLG_Eq.phiInt) '0.0*pi/180'
.ic V(XMTJ2.XLLG_Eq.thInt) '179.9*pi/180'
.ic V(XMTJ2.XLLG_Eq.phiInt) '0.0*pi/180'
```

Example Results (P to AP)

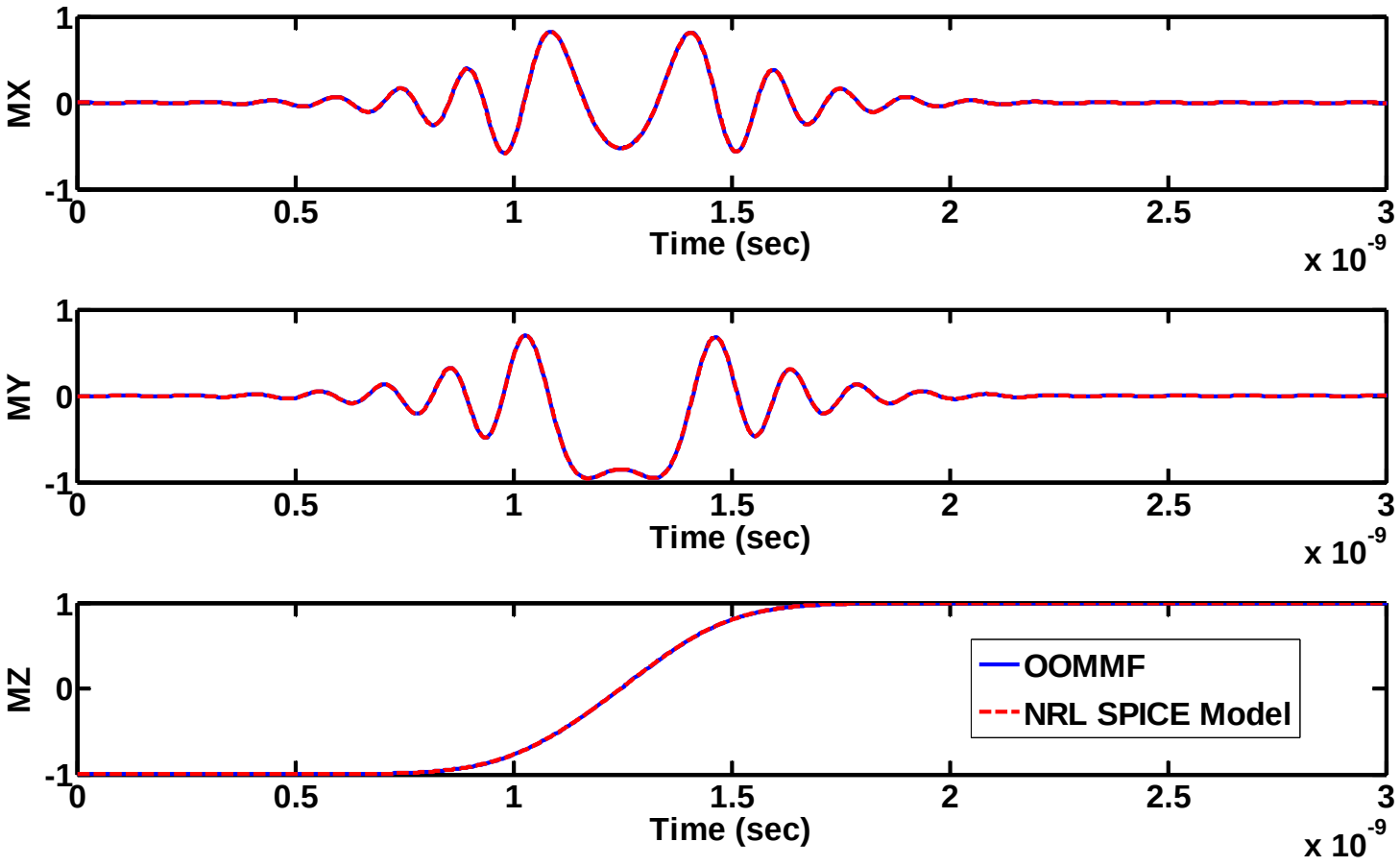
```
*******************************************************************************
***                              Analysis                                   ***
*******************************************************************************
.tran 1p 3.0n START=1e-14 uic
.print tran v(XMTJ1.XLLG_Eq.MX) v(XMTJ1.XLLG_Eq.MY) v(XMTJ1.XLLG_Eq.MZ)
*.print tran v(XMTJ2.XLLG_Eq.MX) v(XMTJ2.XLLG_Eq.MY) v(XMTJ2.XLLG_Eq.MZ)
```



Tested in HSPICE-G-2012.06

Example Results (AP to P)

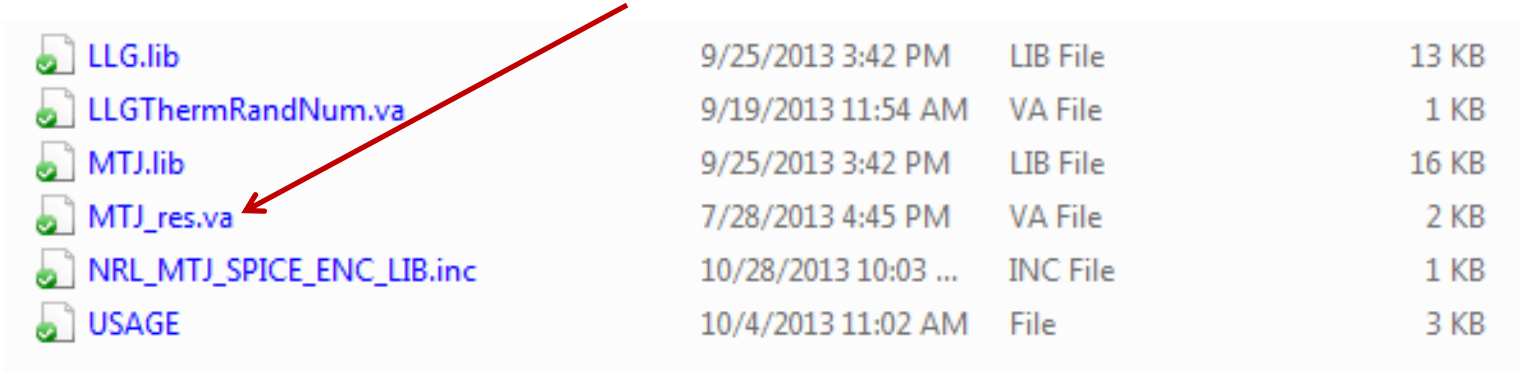
```
*****************************************************************************
***                              Analysis                                 ***
*****************************************************************************
.tran 1p 3.0n START=1e-14 uic
.print tran v(XMTJ1.XLLG_Eq.MX) v(XMTJ1.XLLG_Eq.MY) v(XMTJ1.XLLG_Eq.MZ)
*.print tran v(XMTJ2.XLLG_Eq.MX) v(XMTJ2.XLLG_Eq.MY) v(XMTJ2.XLLG_Eq.MZ)
```



Tested in HSPICE-G-2012.06

How to Change MTJ Resistance Model?

Contains MTJ resistance or I-V characteristic




```
// Creator: Harsha Choday
// Email: schoday@purdue.edu
// Contributors: Xuanyao Fong
// This file is a copy of MTJ_QCOM5_res.va with added comment lines
// Resistance model of MTJ with physical params:
// Eb=0.8, delta=0.75, m_fm=0.735, m_ox=0.74, Ms=800, Ku2=30000
// This file and the coefficients for fitting equation generated by MATLAB

`include "disciplines.vams"
`include "constants.vams"

module MTJ_res(t1,t2,MTJ_curr,th,phi,th_hard,phi_hard);
inout t1,t2;
input th,phi,th_hard,phi_hard;
output MTJ_curr;
electrical t1,t2,MTJ_curr,th,phi,th_hard,phi_hard; //External Terminals of the resistor
```

All terminals must exist!!!

- Module name must be preserved (MTJ_res)
- t1 – free layer
- t2 – pinned layer
- MTJ_curr – current flow from t1 to t2
  - Directionality must be preserved for LLG

How to Change MTJ Resistance Model?

```
**** Wrapper file for including the NRL MTJ SPICE Libraries
** The .hdl needs to point to the file that defines the MTJ resistance model
** (which is defined as MTJ_res)
.hdl "./MTJ_res.va"
** The .lib needs to point to the MTJ_enc.lib file containing the encrypted
** file for defining NRL MTJ SPICE Library components
.lib "./MTJ.lib" NRL_MTJS
```

Point to the file containing your MTJ_res module description

This file needs to be able to locate LLG.lib and LLGThermRandNum.va. It must also know the definition of MTJ_res with the terminals hard coded into the example

```
// Creator: Harsha Choday
// Email: schoday@purdue.edu
// Contributors: Xuanyao Fong
// This file is a copy of MTJ_QCOM5_res.va with added comment lines
// Resistance model of MTJ with physical params:
// Eb=0.8, delta=0.75, m_fm=0.735, m_ox=0.74, Ms=800, Ku2=30000
// This file and the coefficients for fitting equation generated by MATLAB

`include "disciplines.vams"
`include "constants.vams"

module MTJ_res(t1,t2,MTJ_curr,th,phi,th_hard,phi_hard);
inout t1,t2;
input th,phi,th_hard,phi_hard;
output MTJ_curr;
electrical t1,t2,MTJ_curr,th,phi,th_hard,phi_hard; //External Terminals of the resistor
```

All terminals must exist!!!

- Module name must be preserved (MTJ_res)
- t1 – free layer
- t2 – pinned layer
- MTJ_curr – current flow from t1 to t2
  - Directionality must be preserved for LLG

Questions?

C-SPAN

STARnet