2 terminal ferroelectric capacitor CapacitorFerroelectric

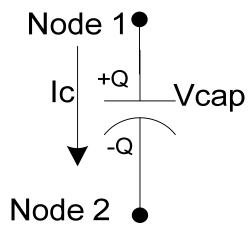


Fig 1: Ferroelectric capacitor element

Form: capacitorferroelectric:<instance name> n1 n2 <parameter list>
n1, n2 are the element terminals

Parameters:

Parameter	Type	Default Value	Required?
epsid: Interfacial capacitance density (F/m^2)	DOUBLE	32e-3	no
epsb0: Bulk capacitance zero-bias permittivity (F/m)	DOUBLE	170	no
a: Area of cross-section of the parallel plate capacitor (m$^{2)}$	DOUBLE	n/a	yes
d: Total capacitor thickness (m)	DOUBLE	n/a	yes
t: 2 * (Interfacial Capacitor thickness at the plate dielectric interface) (m)	DOUBLE	5e-9	no
k: Fringing capacitance constant (F)	DOUBLE	1.6e-15	no
alpha3: Describes the non-linearity of the material in the Landau-Devonshire-Ginzburg model (m^2/C^{2}F)	DOUBLE	3.3e-3	no
T0: Curie-Weiss temperature for a particular BST film thickness (deg C)	DOUBLE	-167	no
T: Current Temperature of the sample (deg C)	DOUBLE	-73	no
beta: Temperature Coefficient of Capacitance (TCC) at zero bias (ppm/deg C)	DOUBLE	600	no
p: Device periphery for fringing capacitance calculations (m)	DOUBLE	n/a	yes

Example:

```
.model c_ferro capacitorferroelectric ( epsid =50e-3 epsb0=170 a=2000e-12 t=5e-9
+ k=2.0e-15 alpha3=3.3e-3 T0=-167 T=-80 beta=1000 p=240e-9)
capacitorferroelectric: cf1 3 0 model=”c_ferro” d=125e-9
```

Details:

This element models a non-linear ferroelectric capacitor. A parallel plate physical model of the capacitor is considered although this concept can be further extended to model ferroelectric IDCs (inter-digitated capacitors) and gap capacitors. This model accounts for interfacial, bulk capacitance and fringing capacitance. It also considers thickness and temperature dependence of the high-permittivity ferroelectric material. This model can be used during time-domain analysis. Leakage and breakdown currents are not modeled.

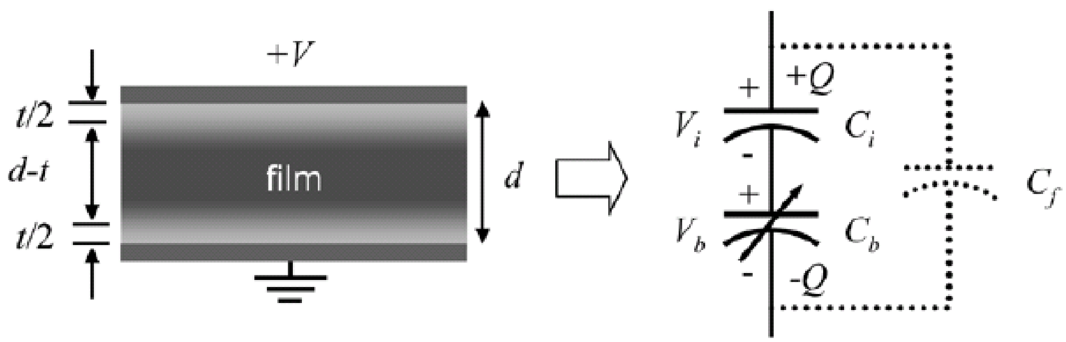


Fig 2: Ferroelectric capacitor model that includes the effect of the interfacial capacitance, bulk capacitance and fringing capacitance[2].

Data collected from experiments indicates that a “dead” layer non-tunable capacitance exists in series with a bulk non-linear capacitance. The voltage applied is dropped across a series combination of the interface capacitance at the two plate dielectric interfaces and the bulk ferroelectric dielectric material. While this model characterizes large area capacitors ($\approx 2000um^2$) very well, small area capacitors need an additional fringing capacitance in parallel as shown in Fig. 2 to account for their reduced tunability compared to large area capacitors[2]. This model ignores the space-charge buildup near the electrodes.

With reference to Fig 2, both the interfacial capacitances are collectively described by a linear charge-voltage equation:

$$V_{i=}\frac{Q}{Ci};Ci=\frac{\varepsilon_i A}{t} \quad (1.1)$$

Here the interfacial capacitance density $\frac{\varepsilon_i}{t}$ is determined experimentally from a series of devices of varying thickness.

The bulk is described by a nonlinear equation from the Landau-Devonshire-Ginzburg (LDG) model [1] by:

$$V_b=\frac{Q}{C_{b,\max}}+KQ^3 \quad (1.2)$$

$$\frac{1}{C_{b,\max}}=\alpha_1\frac{(d-t)}{A} \text{ and } K=\alpha_3\frac{(d-t)}{A} \quad (1.3)$$

The total voltage across the device is then:

$$Vcap=Q(\frac{1}{C_i}+\frac{1}{C_{b,\max}})+KQ^3 \quad (1.4)$$

The fringing capacitance is independent of the field and thickness and is given by

$$C_f=k\frac{P}{d} \quad (1.5)$$

$$\varepsilon_b(T)\approx\varepsilon_{b0}[1-\beta(T-T0)] \quad (1.6)$$

In the equations above

$\varepsilon_i =$ Interfacial material dielectric permittivity (F/m^2)

$\varepsilon_{b0} =$ Bulk dielectric material zero-bias permittivity (F/m)

$A =$ Area of cross-section of the parallel plate capacitor (m^2)

$d =$ Total capacitor thickness (m)

$t =$ Interfacial capacitance thickness (m)

$k =$ Fringing capacitance constant (F)

$\alpha_3 =$ Describes the non-linearity of the material in the Landau-Devonshire-Ginzburg model (m^2/C^2F)

$\varepsilon_b(T) =$ Temperature dependent bulk dielectric zero-bias permittivity (F/m)

$\beta =$ Temperature Coefficient of capacitance (TCC) at zero bias (ppm/deg C)

$T =$ Current Temperature of the sample (deg C)

$T_0 =$ Curie-Weiss temperature for a particular BST film thickness (deg C)

$Q =$ Charge on the capacitor (C)

Netlist file circuit:

The netlist model used to prove the correctness of the model is a RC coupling circuit. The netlist is run with three different values of output resistance ‘R’ to change the RC time-constant of the circuit as shown in the fig 3. The input square wave changes shape based on the RC time constant in comparison with the ‘T’ – the time period of the square wave.

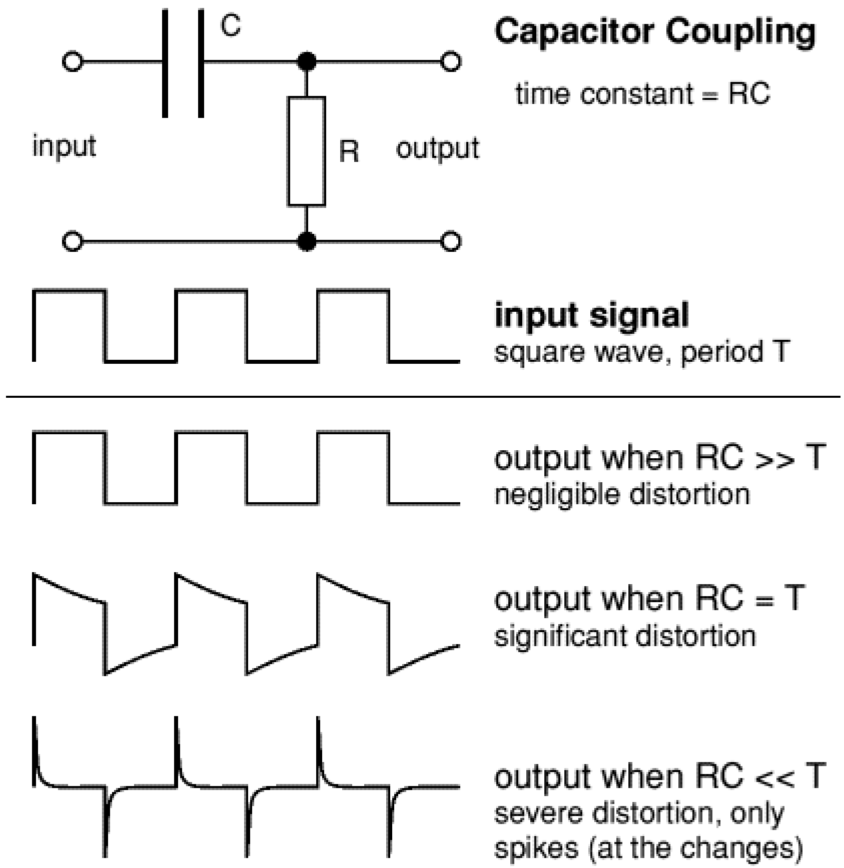


Fig3. Input square wave and output signal wave shapes based on the RC time constant value in comparison with ‘T’ – the time period of the wave [6].

Example of Transient analysis (.TRAN2) Fixed time steps, time-stepping nonlinear analysis

<u>Netlist File:</u>

*** Transient Analysis for the Ferroelectric capacitor

.options verbose

```
*.svtr  tstop = 2e-5 n_freqs = 70 tstep = 0.25e-6
*.svtr  tstop = 1e-4 n_freqs = 70 tstep = 0.25e-6

.tran2 tstop = 1e-4 tstep = 0.50e-6 out_steps=1 im=2


*vsource:1 1 0 vac=1.0 f=0.3e5 phase=90

vpulse:v1 1 0 v1=0 v2=5 td=0 tr=0.05e-5 tf=0.05e-5 pw=1.5e-5 per=3.5e-5
capacitorferroelectric:cf1 1 2 a=6500e-12 d=150e-9 p=160e-9

*RC time constant << T
*resistor:rin1 2 0 r=1000

*RC time constant ~ T
*resistor:rin1 2 0 r=25000

*RC time constant >> T
resistor:rin1 2 0 r=1000000

.options gnuplot
*.options postamble1 = "using 2:3"

.options plotVT1Preamble="set term x11 font 'helvetica,13';
set title 'Ferroelectric capacitor Voltage';
set xlabel 'TIME (microseconds)'; set ylabel 'VOLTAGE (V)'"
.out plot element "capacitorferroelectric:cf1" 0 ut 1e6 scalex plotVT1Preamble in
"capacitorferroelectric_v.out"

.options plotVT1Preamble="set term x11 font 'helvetica,13';
set title 'Ferroelectric capacitor Current';
set xlabel 'TIME (microseconds)'; set ylabel 'Current (A)'"
.out plot element "capacitorferroelectric:cf1" 0 it 1e6 scalex plotVT1Preamble in
"capacitorferroelectric_i.out"

.options plotVT1Preamble="set term x11 font 'helvetica,13';
set title 'Input Voltage Source';
set xlabel 'TIME (microseconds)'; set ylabel 'Voltage (V)'"
.out plot term 1 vt 1e6 scalex plotVT1Preamble in "source_v.out"

.options plotVT1Preamble="set term x11 font 'helvetica,13';
set title 'Voltage across resistor';
set xlabel 'TIME (microseconds)'; set ylabel 'Voltage (V)'"
.out plot term 2 vt 1e6 scalex plotVT1Preamble in "res_v.out"

*pack in "capacitorferroelectric_combo.out"
```

```
*.out plot "capacitorferroelectric_combo.out" postamble
**.out plot element "capacitorferroelectric22:cf1" 0 xt in "capacitorferroelectric_x.out"
*.out plot element "capacitorferroelectric22:cf1" 0 ut stripx in
"capacitorferroelectric_v.out"
.end
```

Log File:

```
**********  fREEDA 1.3 running on Sun Apr 20 22:54:49 2008  **********


   *** Parsing input netlist ...

   *** Expanding subcircuits ... done.

   *** Initializing Elements ...cmax: 2.08002e-10
 done.

   *** Checking reference terminals ... done.

   *** Starting analysis ...

---------------------------------------------------------------------------
   Matrix size = 3
   Matrix nnz = 6
   equed = 7.95719e-305
   recip_pivot_growth = 1
   1 / Condition number = 0.840131
   info = 0
   ferr = 9.70941e-308
   berr = 1
   No of nonzeros in factor L = 6
   No of nonzeros in factor U = 6
   No of nonzeros in L+U = 9
   L\U MB 0.000          total MB needed 0.001          expansions 0
   Using line search method.
   Nonlinear analysis tolerance (ftol) = 6.12865e-06
   Maximum number of nonlinear iterations per time-point (maxit) = 250
   Using Lee and Lee's quasi-Newton updates.
   --- Starting transient simulation ...

   Number of nonlinear state variables: 1
--------------------------------------------------------------------------------------
   |  Step |    Time (s)       |   Residual       |  Recent Max       |     Max           |
--------------------------------------------------------------------------------------
   |      0  | 0.000000e+00 | 0.000000e+00 | 0.000000e+00 *| 0.000000e+00 |
   |      1  | 5.000000e-07 | 6.274981e-13 | 6.274981e-13     | 6.274981e-13  |
```

2	1.000000e-06	1.785239e-13	1.785239e-13	6.274981e-13
3	1.500000e-06	1.865175e-14	1.865175e-14	6.274981e-13
4	2.000000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
5	2.500000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
6	3.000000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
7	3.500000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
8	4.000000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
9	4.500000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
10	5.000000e-06	1.152591e-01	1.152591e-01 *	1.152591e-01
:	:	:	:	:
:	:	:	:	:
190	9.500000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
191	9.550000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
192	9.600000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
193	9.650000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
194	9.700000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
195	9.750000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
196	9.800000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
197	9.850000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
198	9.900000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
199	9.950000e-05	1.124087e-01	1.124087e-01 *	1.152591e-01
200	1.000000e-04	1.124087e-01	1.124087e-01 *	1.152591e-01

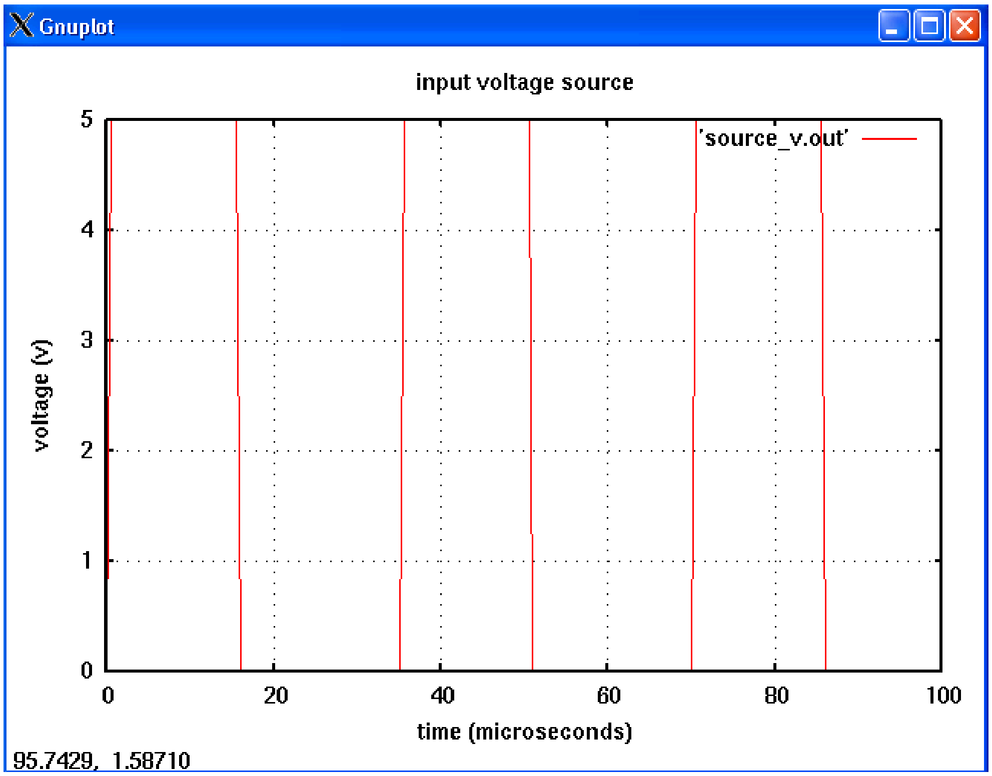
--- Maximum Residual: 0.115259

Plotting output file: capacitorferroelectric_v.out.
Plotting output file: capacitorferroelectric_i.out.
Plotting output file: source_v.out.
Plotting output file: res_v.out.

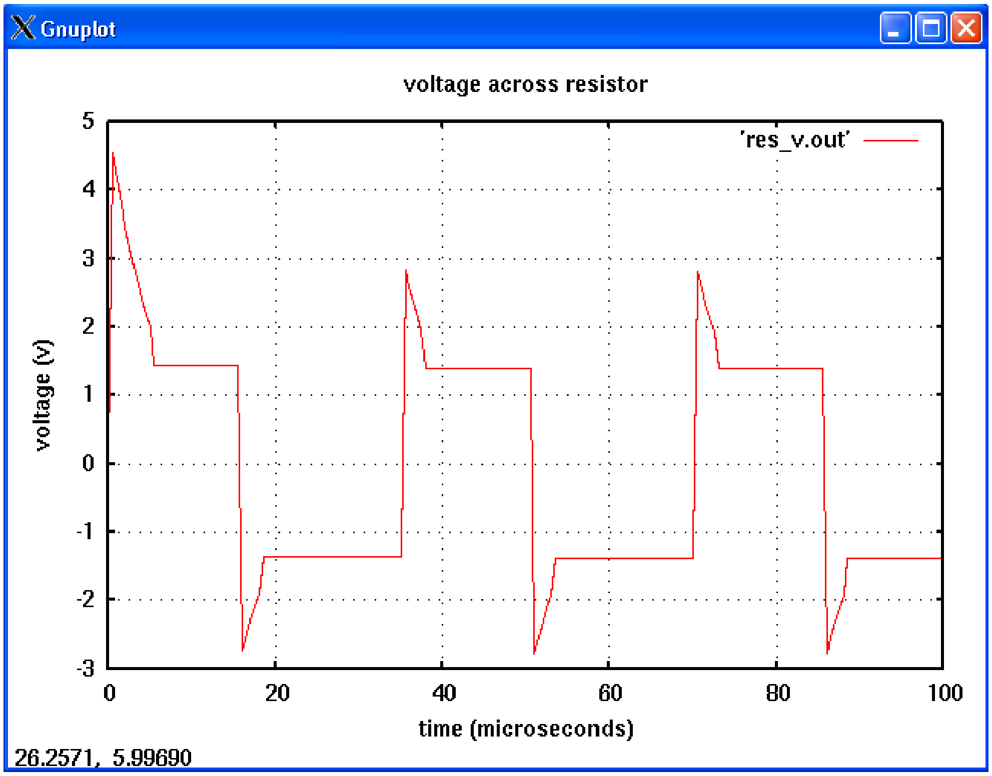
************** fREEDA 1.3 stopping on Sun Apr 20 22:54:52 2008 ***********

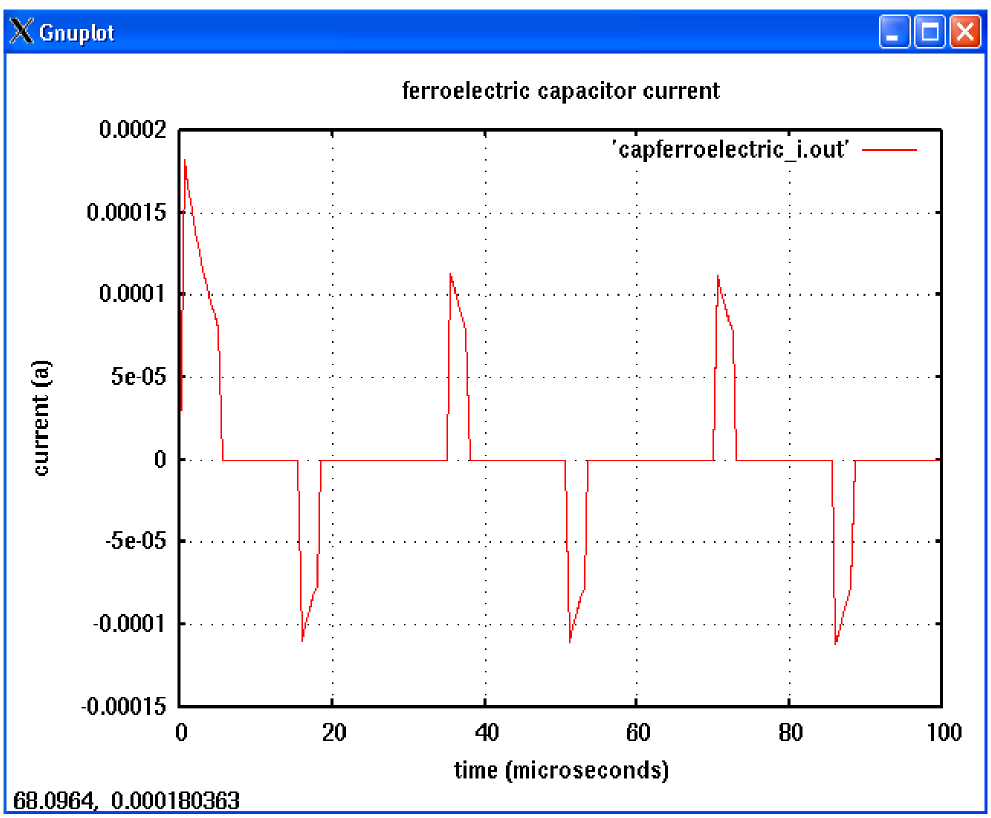
Simulation Results in fREEDA:

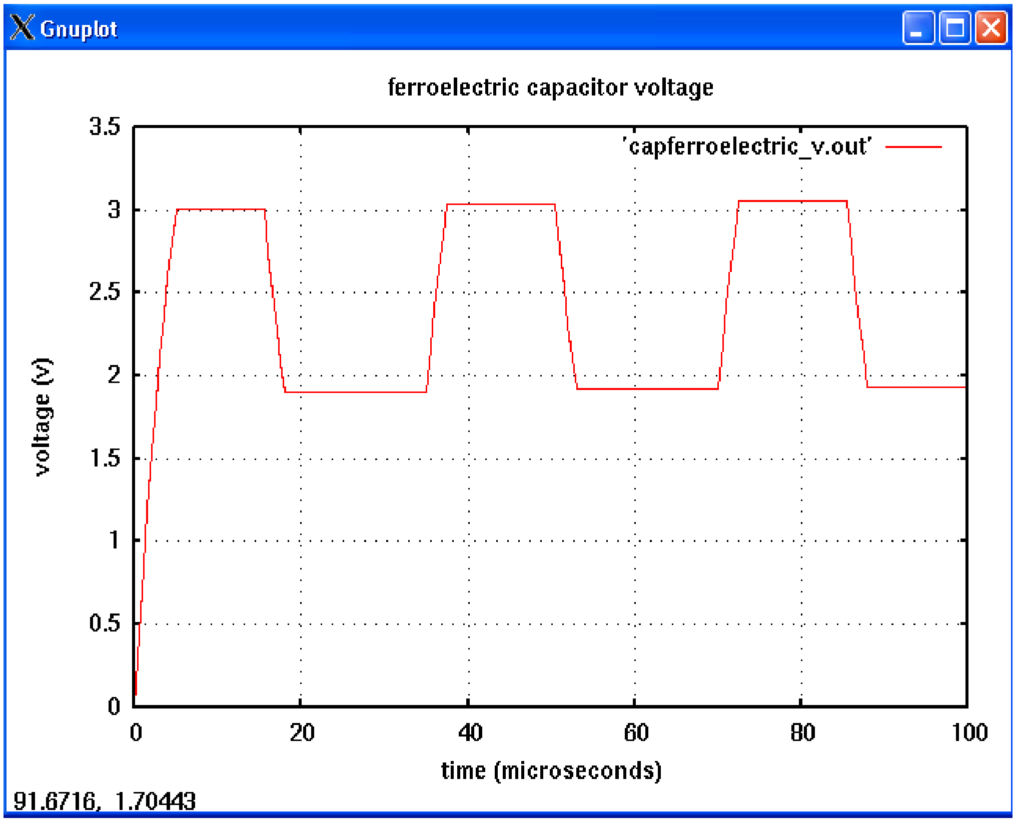
Input Voltage Pulse:



RC time constant ~ T:

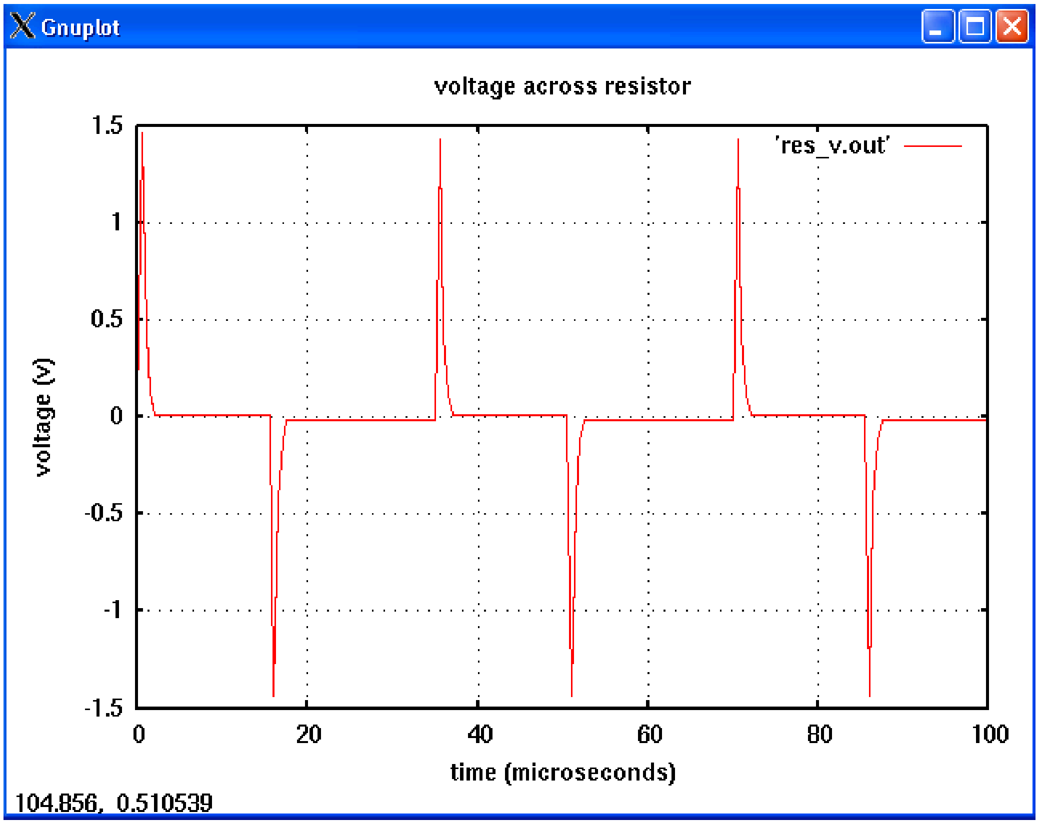


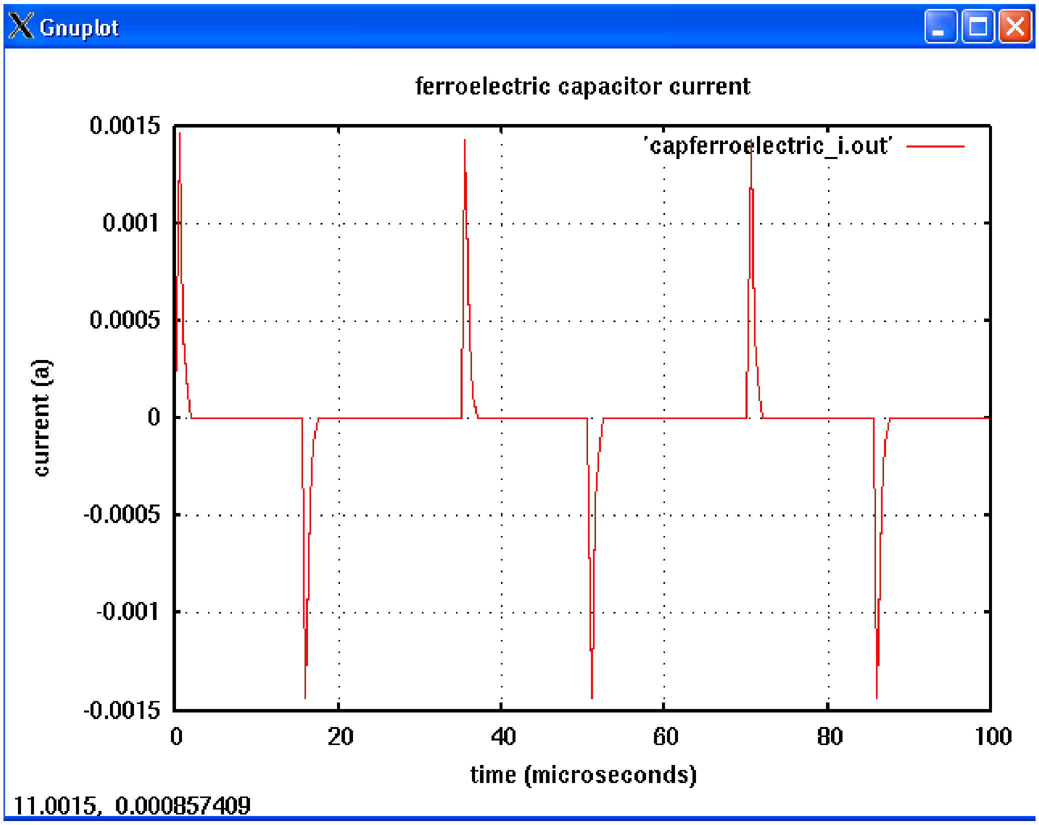


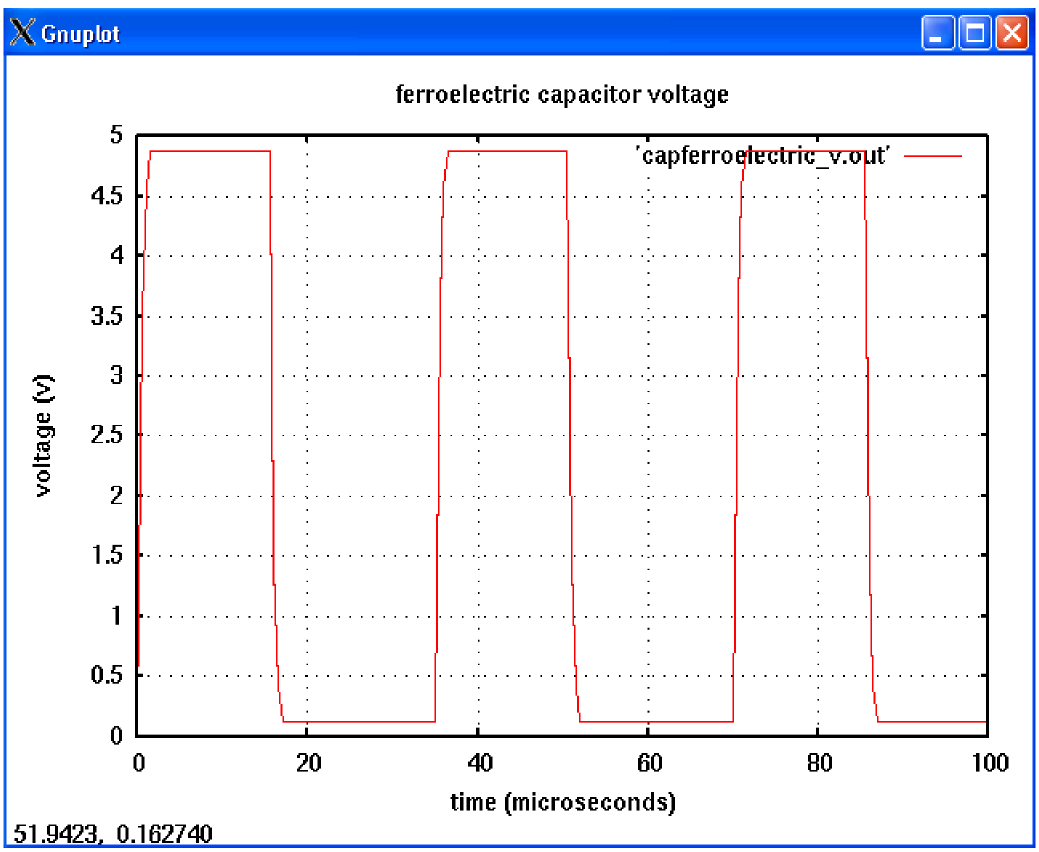


Gnuplot
ferroelectric capacitor voltage
'capferroelectric_v.out'
voltage (v)
time (microseconds)
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
91.6716, 1.70443

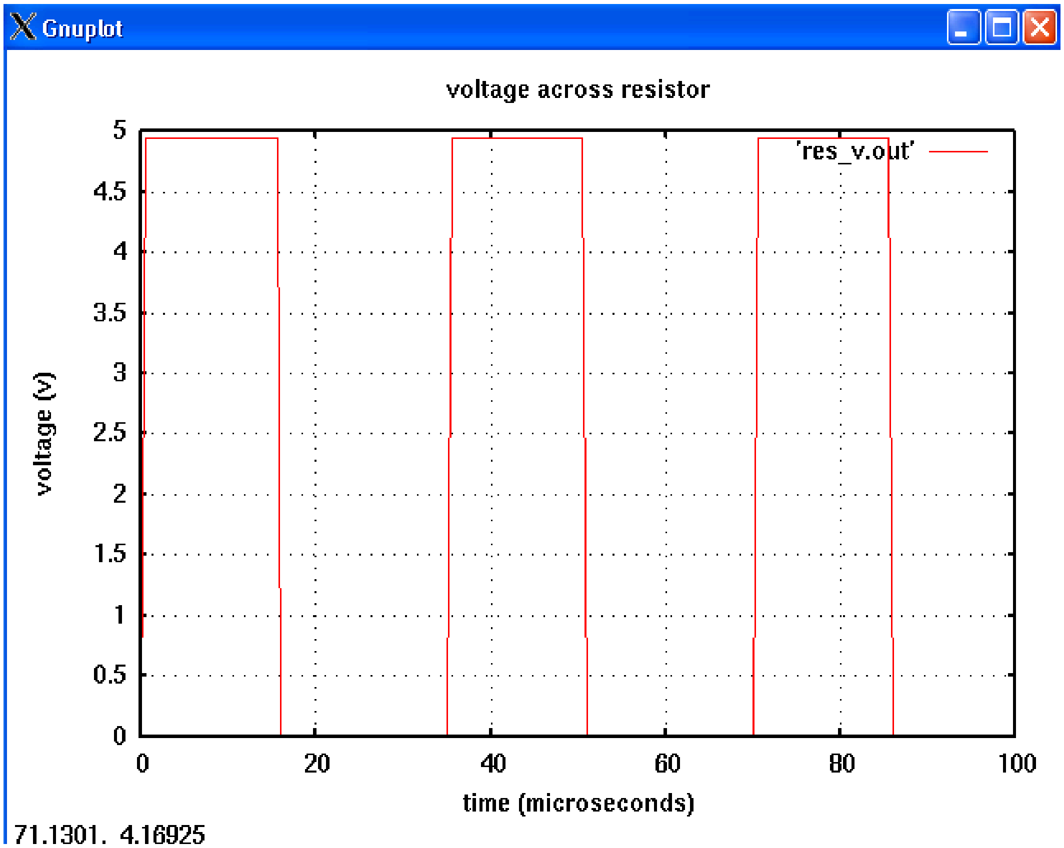
RC time constant << T:

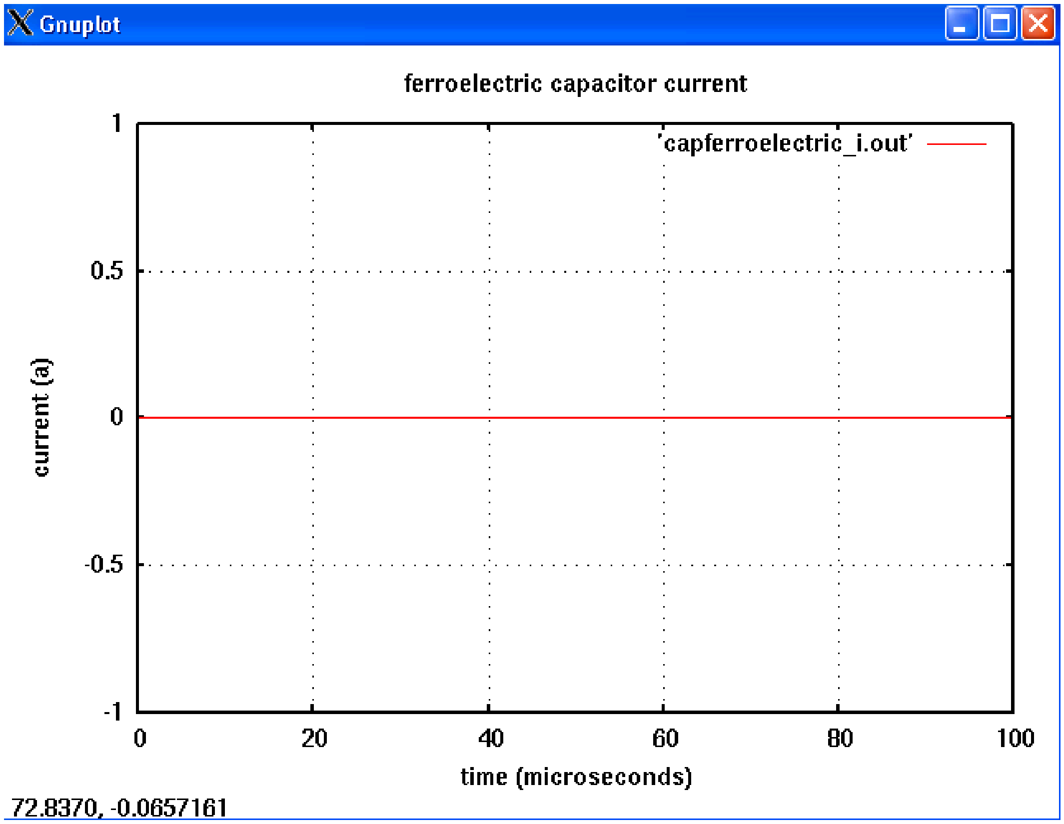


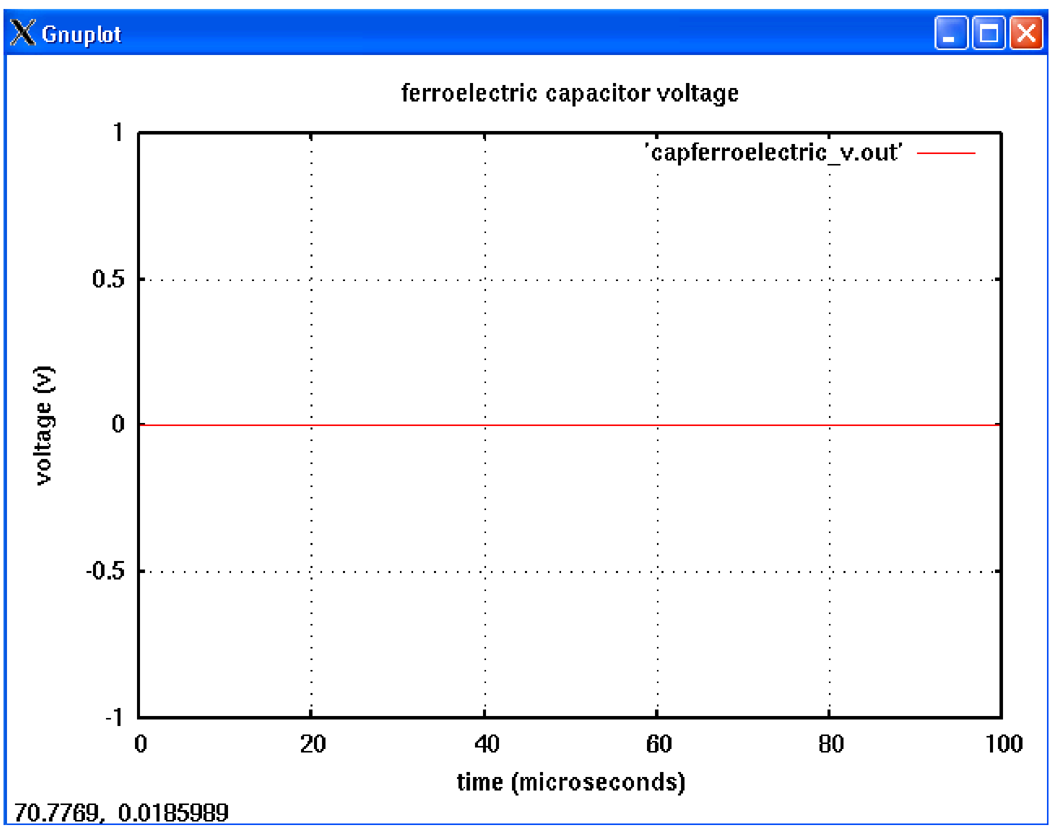

Gnuplot
ferroelectric capacitor current
'capferroelectric_i.out'
current (a)
0.0015
0.001
0.0005
0
-0.0005
-0.001
-0.0015
0
20
40
60
80
100
time (microseconds)
11.0015, 0.000857409


Gnuplot
ferroelectric capacitor voltage
'capferroelectric_v.out'
voltage (v)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
time (microseconds)
51.9423, 0.162740

<u>RC time constant >> T:</u>




Gnuplot
ferroelectric capacitor current
'capferroelectric_i.out'
current (a)
1
0.5
0
-0.5
-1
0
20
40
60
80
100
time (microseconds)
72.8370, -0.0657161


Gnuplot
ferroelectric capacitor voltage
'capferroelectric_v.out'
voltage (v)
1
0.5
0
-0.5
-1
0
20
40
60
80
100
time (microseconds)
70.7769, 0.0185989

Version:
2008.04.20(2008 April 20)

Credits:

Name	Affiliation	Date	Links
Vrinda Haridasan vharida@ncsu.edu	NC State University	April 2008	NC STATE UNIVERSITY www.ncsu.edu

References:

[1] David R. Chase, Lee-Yin Chen, Robert York, "Modeling the Capacitive Nonlinearity in Thin-Film BST Varactors", IEEE MTT-S Vol 53 Oct, 2005.
[2] Michael B. Steer, W. Devereux Palmer, Robert York, "Multifunctional Adaptive Microwave Circuits and systems", Chap 4, 2008 Edition
[3] S.K. Streiffer, Cem Basceri, C.B. Parker, S.E.Lash, Angus I. Kingon, "Ferroelectricity in thin films: The dielectric response of fiber-textured (Ba_xSr_{1-x})$Ti_{1+y}O$ thin films grown by chemical vapor deposition", J. Appl. Phys, Vol 86, N0.8, Oct 1999
[4] Cem Basceri, S.K. Streiffer, Angus I. Kingon, "The dielectric response as a function of temperature and film thickness of fiber-textured (Ba,Sr)TiO_3 thin films grown by chemical vapor deposition, J. Appl. Phys Vol 82, Sept 1997
[5] J.D.Baniecki, T.Shioga, K. Kurihara, N.Kamehara, "A study of current transport in thin-film capacitors containing a voltage-dependent interface state charge distribution.", J. Appl Phys, Vol 97, May 2005
[6] http://www.kpsec.freeuk.com/capacit.htm