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NEEDS Simulation-ready Compact Models

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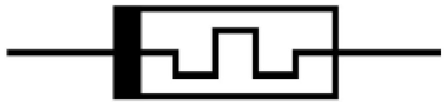
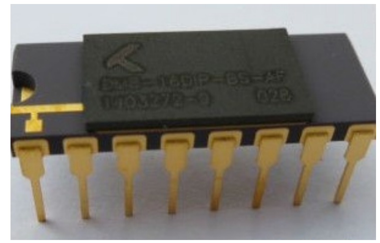
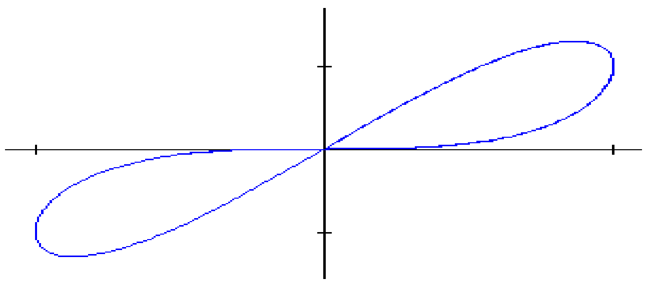
Compact Models for Simulation



memristor

(RRAM, CBRAM, PCM...)



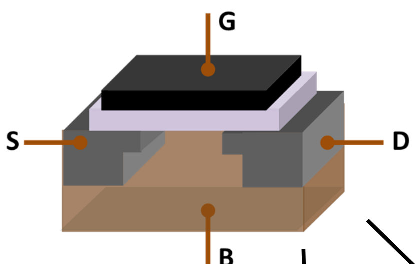


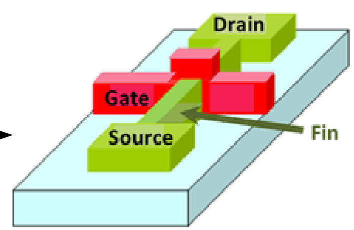
Applications:

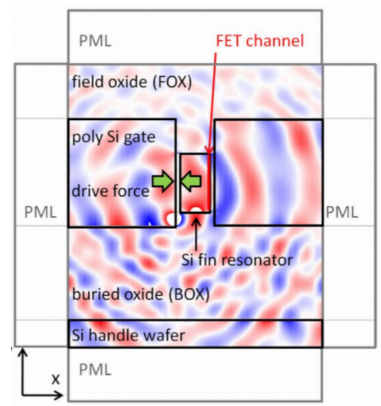
computation

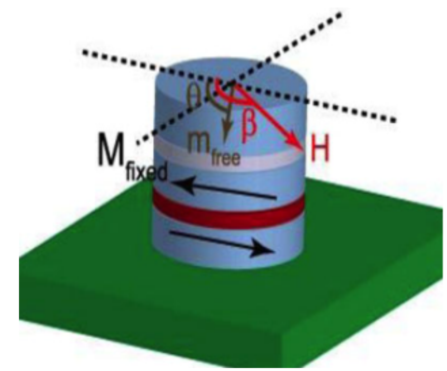
communication

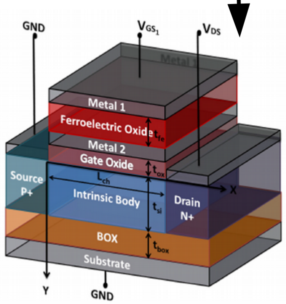
energy systems

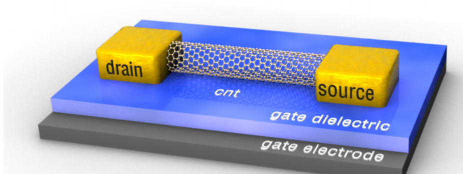


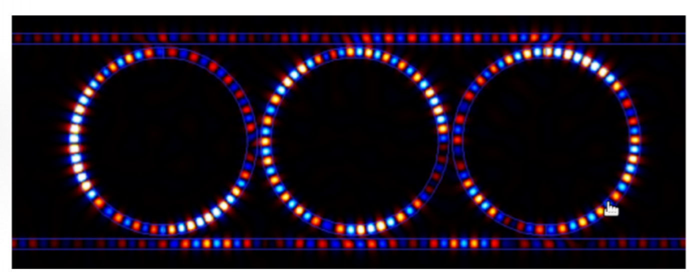


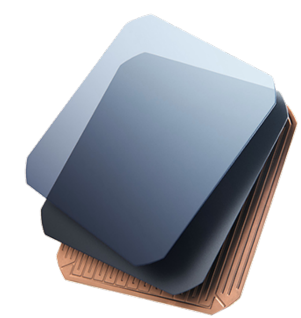






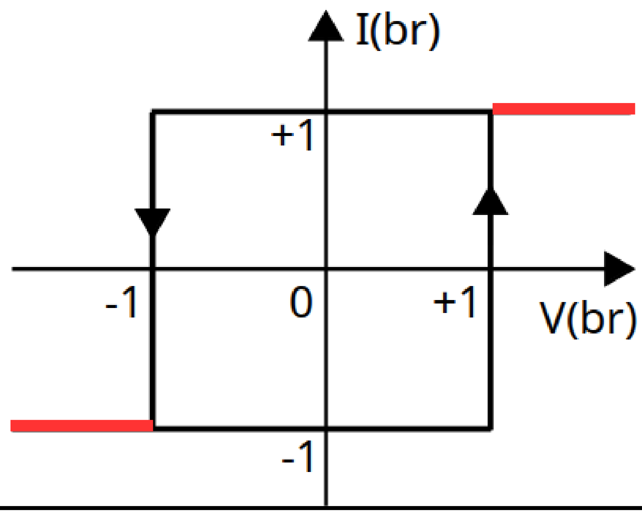






Compact Models for Simulation

not




```
$bound_step(tstep);
c_time = $abstime;
dt = c_time - p_time;
x = x_last + dt * exp(…);
```

```
$rdist_normal(rand_seed, 0);
```

```
@(initial_step) begin
    x = x_init;
end
```

only for TRAN

none works for DC, AC, PSS

```
real i;
analog begin
     if V(br) < -1
          i = -1;
     if V(br) > +1
          i = +1;
     I(br) <+ i;
end
```

"memory state"

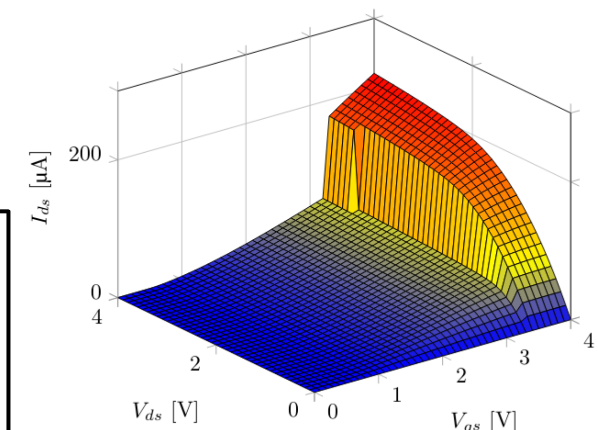
"hidden state"

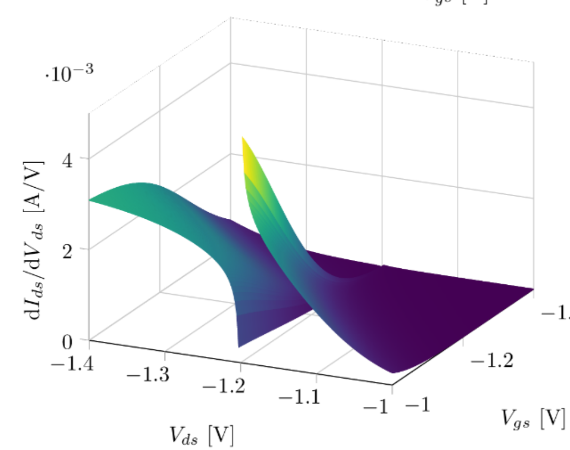
```
int isON = 0;
if (abs(V(…)) > V_snap)
   isON = 1;
if (isON) {
   ...
} else {
   ...
}
```

Boolean variable

"hybrid model"

not an analog compact model

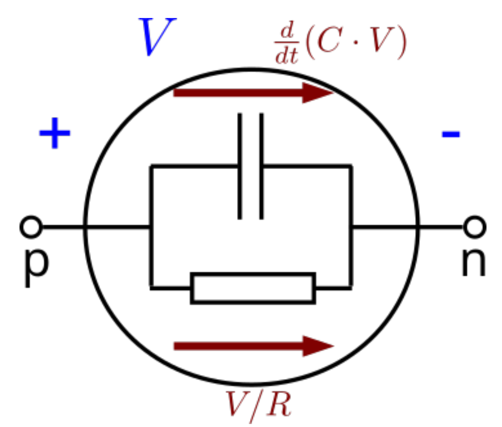




Good Compact Models

- "simulation-ready"
  - run in all analyses (DC/AC/TRAN/sensitivity/shooting/HB/…)
  - run in all simulators **consistently** ~~analysis-specific code~~
- a simple (trivial) example

```
...
I(p, n) <+ V(p, n)/R;
I(p, n) <+ ddt(C * V(p, n));
...
```



  - differential equation format

$$\text{ipn} = \frac{d}{dt} q(\text{vpn}) + f(\text{vpn})$$

  "charges" and "currents", continuous and smooth

  - no $abstime, idt(), @initial_step, @cross, $bound_step, $rdist_normal *etc.*
  - well-posed

Mahmutoglu/Wang/Gupta/Roychowdhury (2017) "Well-Posed Device Models for Electrical Circuit Simulation"

Good Compact Models

- Well-posedness: https://en.wikipedia.org/wiki/Well-posed_problem
  - a solution exists
  - the solution is unique
  - the solution's behavior changes continuously with the initial conditions.

  original definition applies to problems/analyses, not models

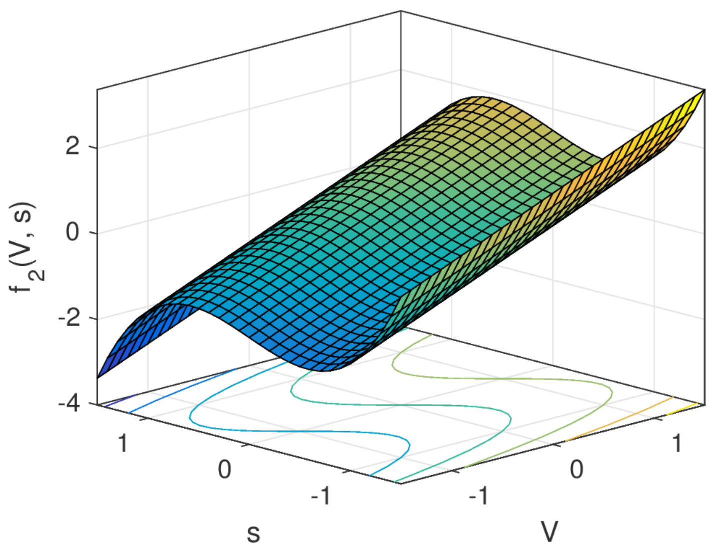
- finite and unique outputs
  - 1/(x-a), log(x), sqrt(x), …
  - random number generation for noise and variability?
- continuous and smooth
  - C^∞: hgher-order derivatives for PSS, distortion, homotopy
- input range
  - *should a model evaluate at 1000V?*
- higher-level requirements
  - well-understood physics, well-formulated (in DAE), well-tested
  - well-written in Verilog-A

Good Verilog-A Practices

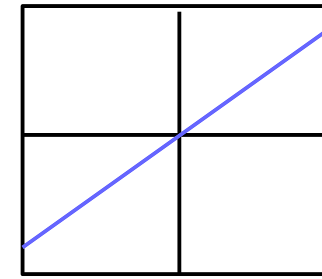
- DO use branches.
- DO declare and initialize all variables and DO NOT use memory states.
- DO NOT use event control statements.
- DO NOT use analysis dependent functions.
- DO use ddt, but only in allowed ways.
- DO NOT use idt.
- DO NOT use time-varying functions.
- DO NOT use random number generators.
- DO take great care when using implicit equations.
- DO NOT allow any nodes in your model without having at least one branch with a well-defined contribution attached to it.
- DO NOT use bias-dependent switch branch and node collapse conditions.
- DO use parameter ranges.

Colin McAndrew et al, "Best Practices for Compact Modeling in Verilog-A"
Geoffrey Coram, "How to (and how not to) write a compact model in Verilog-A"
A.G. Mahmutoglu et al, "Well-Posed Device Models for Electrical Circuit Simulation"

Case Study: Devices with Hysteresis



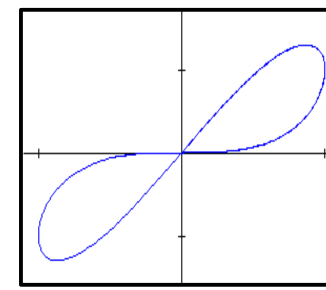
$$\textcolor{red}{\mathbf{ipn}} = f\left(\textcolor{blue}{\mathbf{vpn}}\right)$$



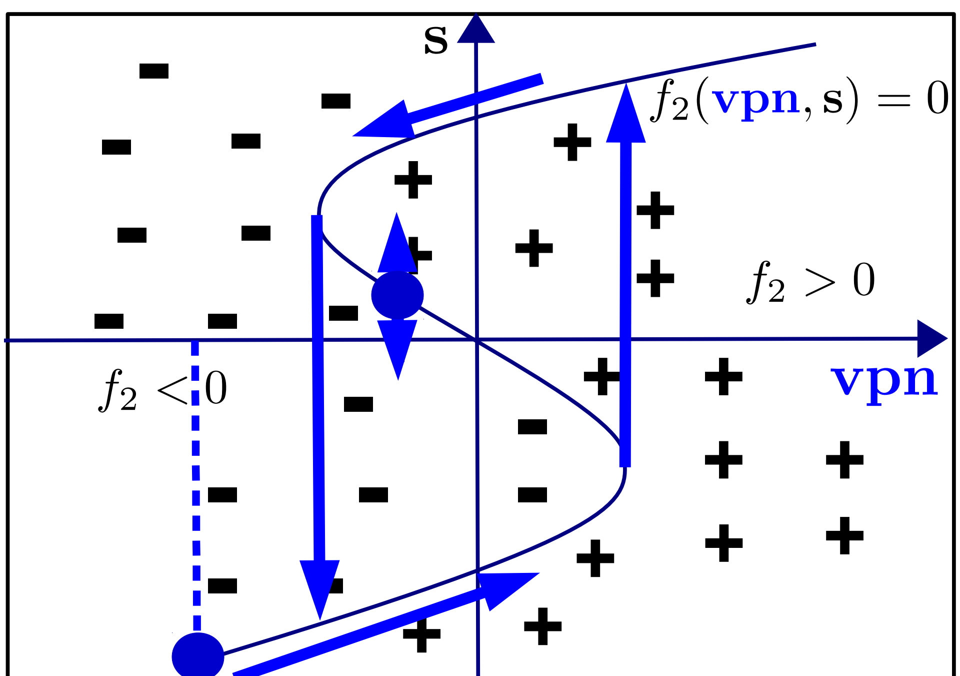
$$\Updownarrow$$

$$\textcolor{red}{\mathbf{ipn}} = f_1\left(\textcolor{blue}{\mathbf{vpn}},\ \mathbf{s}\right)$$

$$\frac{d}{dt}\mathbf{s} = f_2\left(\textcolor{blue}{\mathbf{vpn}},\ \mathbf{s}\right)$$



internal state variable “memory”



Example:

$$f_1\left(\textcolor{blue}{\mathbf{vpn}},\ \mathbf{s}\right) = \frac{\textcolor{blue}{\mathbf{vpn}}}{R} \cdot (1 + \tanh(\mathbf{s}))$$

$$f_2\left(\textcolor{blue}{\mathbf{vpn}},\ \mathbf{s}\right) = \textcolor{blue}{\mathbf{vpn}} - \mathbf{s}^3 + \mathbf{s}$$

hysteresis ≠ discontinuity or if-else

hysteresis ≠ $abstime, ≠ hybrid models

Case Study: Devices with Hysteresis

Template:

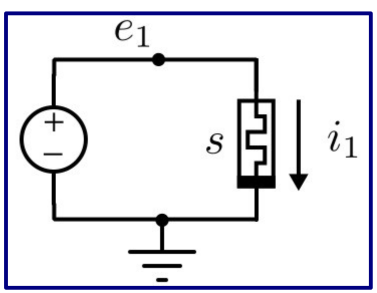
$$\mathbf{ipn} = f_1\left(\mathbf{vpn},\ \mathbf{s}\right)$$

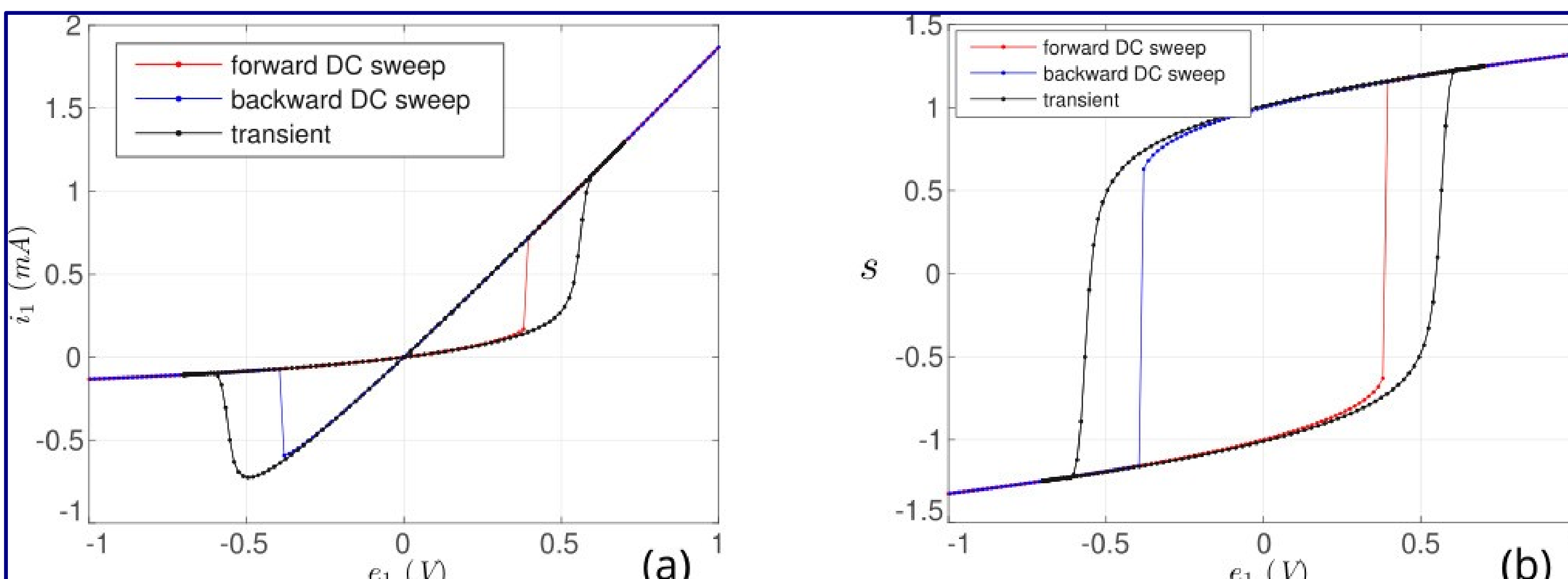
$$\frac{d}{dt}\mathbf{s} = f_2\left(\mathbf{vpn},\ \mathbf{s}\right)$$

MAPP:

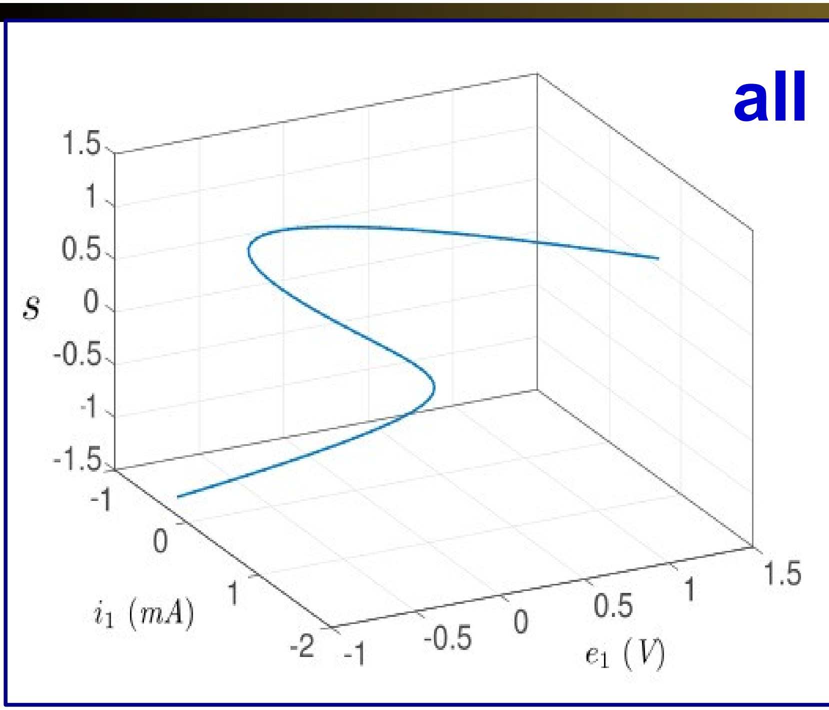
$$\mathbf{ipn} = \frac{d}{dt}\underbrace{q_e\left(\mathbf{vpn},\ \mathbf{s}\right)}_{\mathbf{0}} + \underbrace{f_e\left(\mathbf{vpn},\ \mathbf{s}\right)}_{f_1}$$

$$0 = \frac{d}{dt}\underbrace{q_i\left(\mathbf{vpn},\ \mathbf{s}\right)}_{-\mathbf{s}} + \underbrace{f_i\left(\mathbf{vpn},\ \mathbf{s}\right)}_{f_2}$$





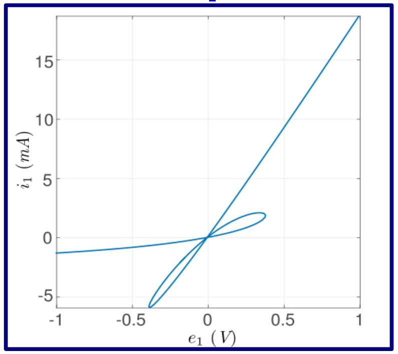
Case Study: Devices with Hysteresis



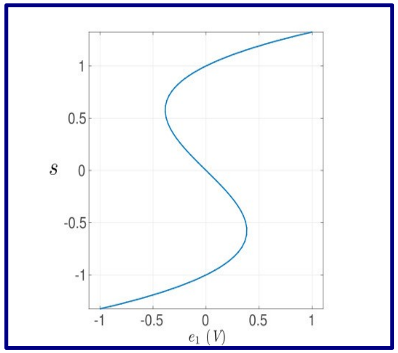
all DC sols from homotopy analysis

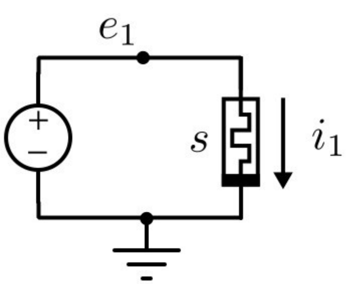
(like a curve tracer)

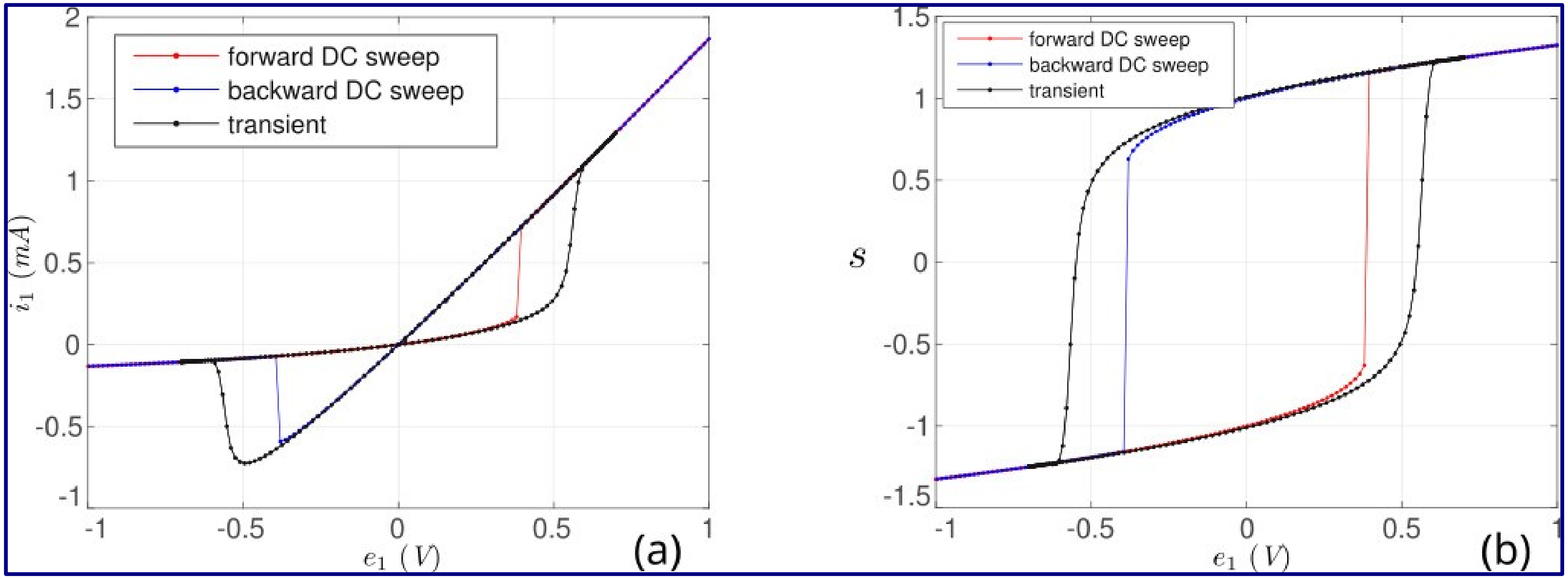
top



side







Internal Unknowns in Verilog-A

$$\mathbf{ipn} = \frac{\mathbf{vpn}}{R} \cdot (1 + \tanh(\mathbf{s}))$$

$$\frac{d}{dt}(\tau \cdot \mathbf{s}) = \mathbf{vpn} - \mathbf{s}^3 + \mathbf{s}$$

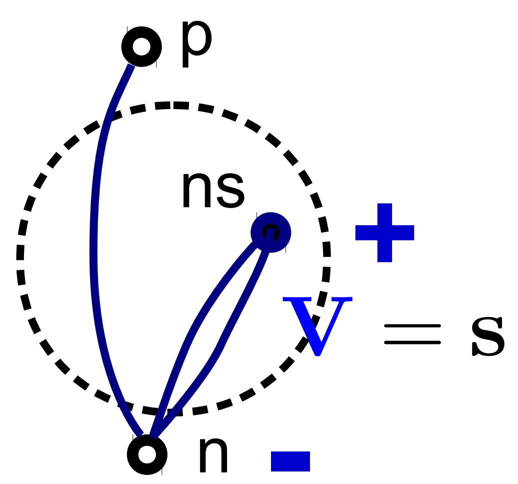
use a potential or flow

```
`include "disciplines.vams"
module hys(p, n);
    inout p, n;
    electrical p, n, ns;
    branch (ns, n) ns_br1;
    branch (ns, n) ns_br2;
    parameter real R = 1e3 from (0:inf);
    parameter real k = 1 from (0:inf);
    parameter real tau = 1e-5 from (0:inf);
    real s;

    analog begin
        s = V(ns, n);
        I(p, n)   <+ V(p, n)/R * (1+tanh(k*s));
        I(ns_br1) <+ V(p, n) - pow(s, 3) + s;
        I(ns_br2) <+ ddt(-tau*s);
    end
endmodule
```

internal node

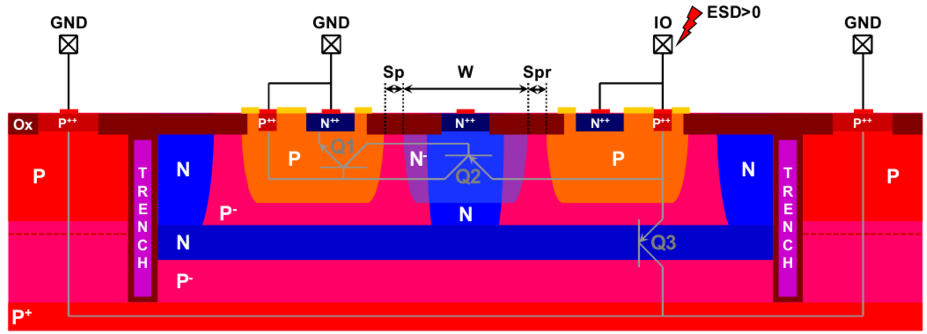
internal unknown

implicit differential equation

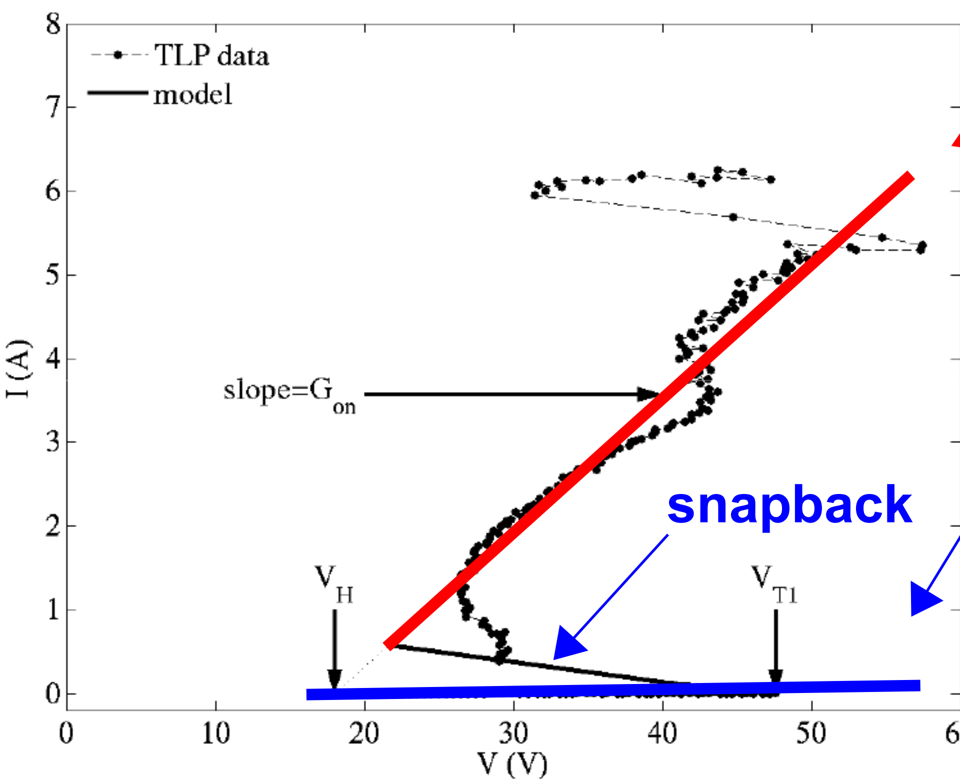


ESD Snapback Model

ESD protection device



Gendron, et al. "New High Voltage ESD Protection Devices based on Bipolar Transistors for Automotive Applications." IEEE EOS/ESD Symposium, 2011.



Ida/McAndrew. "A Physically-based Behavioral Snapback Model." IEEE EOS/ESD Symposium, 2012.

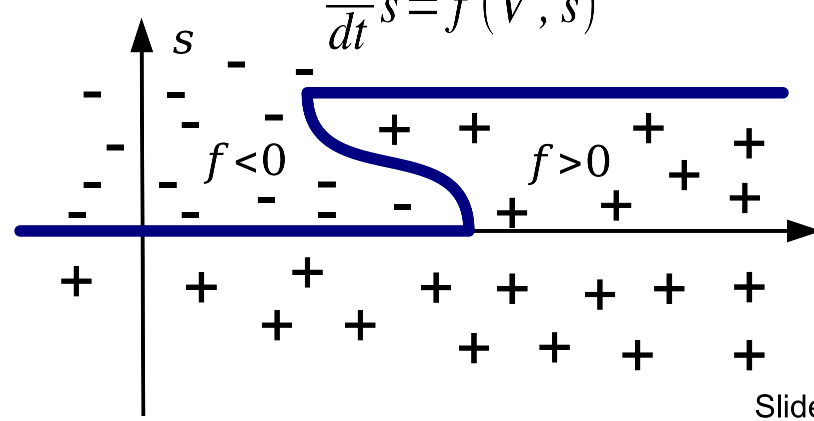
$$I_{on} = G_{on} \cdot (V - V_H)$$

$$I_{off} = I_S \cdot \left(1 - e^{-V/\phi_T}\right) \cdot \sqrt{1 + \frac{max(V, 0)}{V_D}}$$

$$I = s \cdot I_{on} + I_{off}$$

internal state: indicator of impact ionization

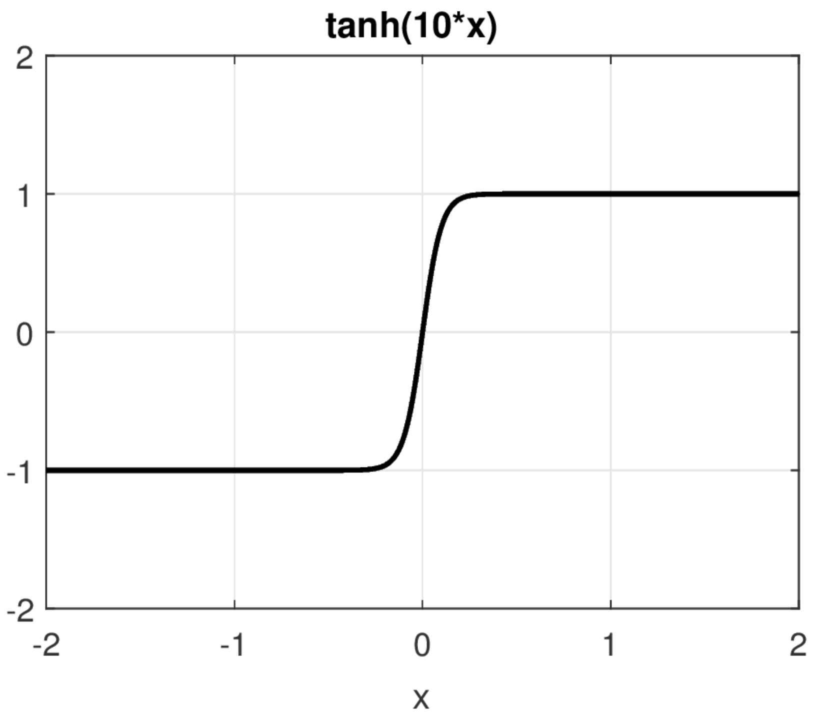
$$\frac{d}{dt} s = f(V, s)$$

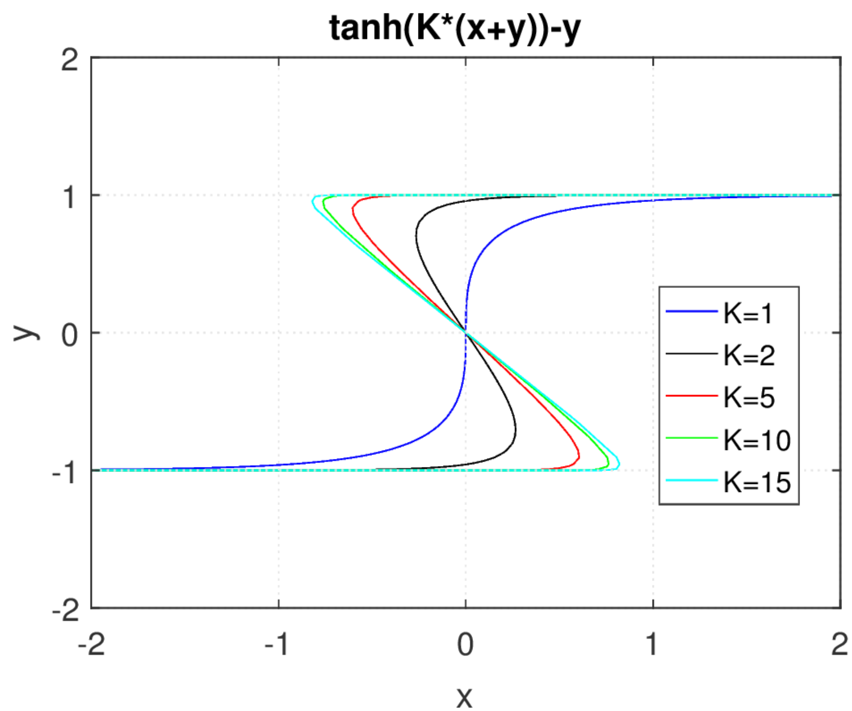


ESD Snapback Model

$$\frac{d}{dt} s = f\left(V, s\right)$$

many possible functions






```
...
Vstar = 2*(V(p, n)-0.5*VT1-0.5*VIH)/(VT1-VIH);
sstar = 2*(s-0.5);
I(ns, n) <+ tanh(K*(Vstar + sstar)) - sstar;
...
```

shift transition points

shift range to (0, 1)

ESD Snapback Model

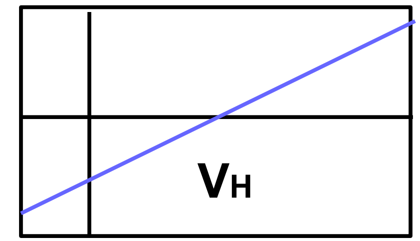
```
`include "disciplines.vams"

module ESDclamp(p, n);
    inout p, n;
    electrical p, n, ns;

    parameter real Gon = 0.1 from (0:inf);
    ...

    analog begin
        s = V(ns, n);
        Ion = smoothclip(Gon*(V(p, n)-VH), smoothing)
                    - smoothclip(-Gon*VH, smoothing);
        Ioff = Is * (1 - limexp(-V(p, n)/VT))
                     * sqrt(1 + max(V(p, n), 0)/VD);
        I(p, n) <+ Ioff + pow(s, Alpha) * Ion;
        I(p, n) <+ ddt(C * V(p, n));

        Vstar = 2*(V(p, n)-0.5*VT1-0.5*VIH)/(VT1-VIH);
        sstar = 2*(s-0.5);
        I(ns, n) <+ tanh(K*(Vstar + sstar)) - sstar;
        I(ns, n) <+ ddt(-tau*s);
    end
endmodule
```

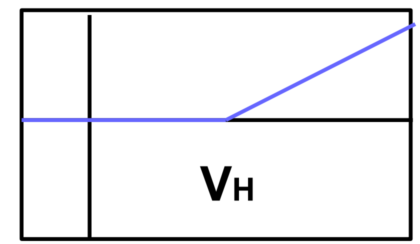
internal unknown as a voltage

Ion

Ioff

implicit differential equation



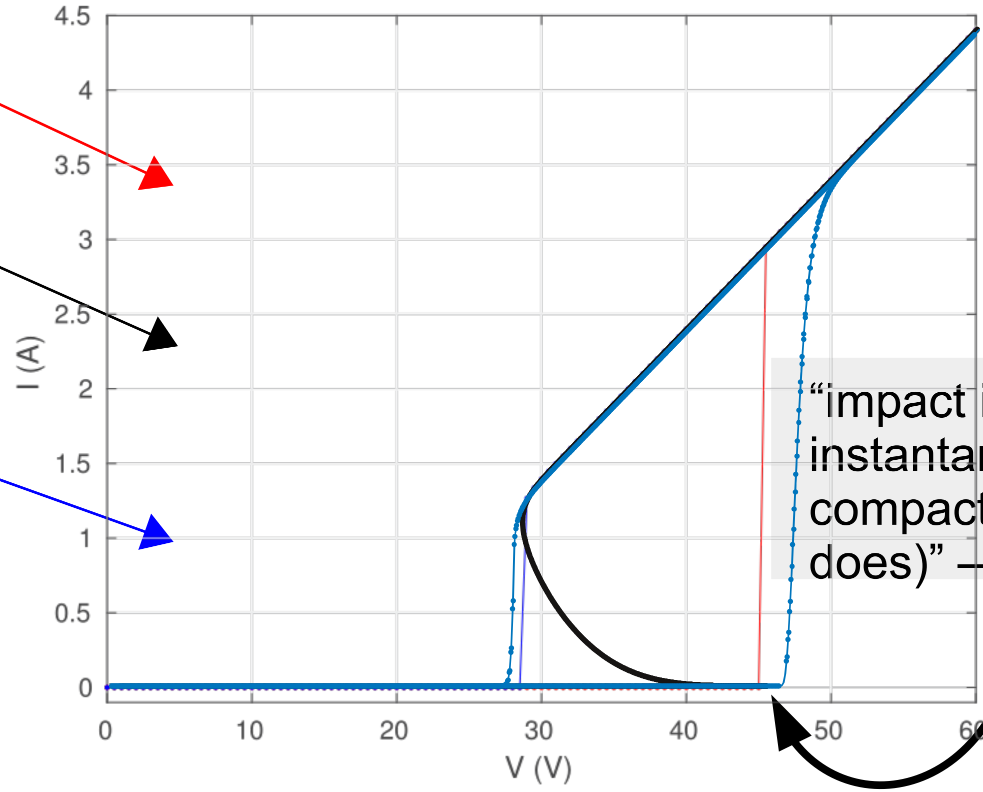


ESD Snapback Model

forward/backward DC sweeps

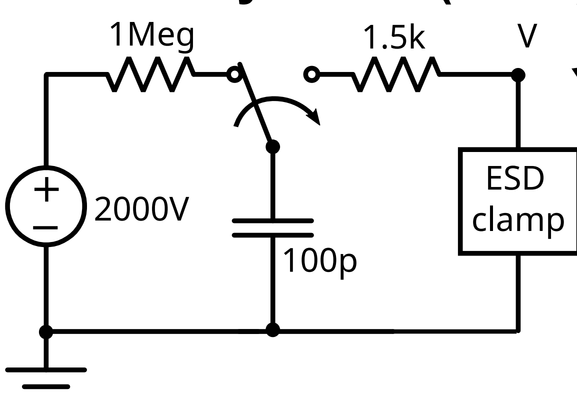
homotopy (all DC sols)

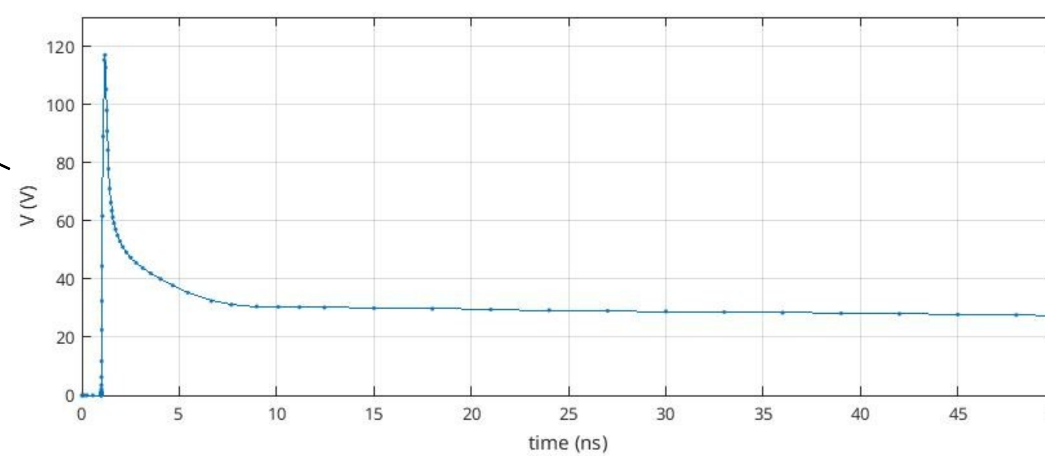
transient voltage sweeps



"impact ionization doesn't happen instantaneously (although all compact models assume that it does)" –- C.C. McAndrew

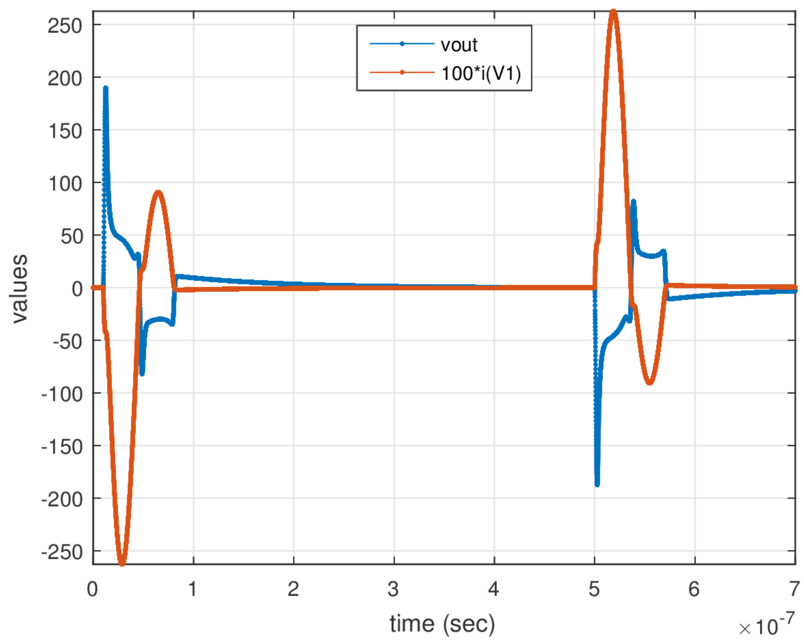
Human Body Mode (HBM) test



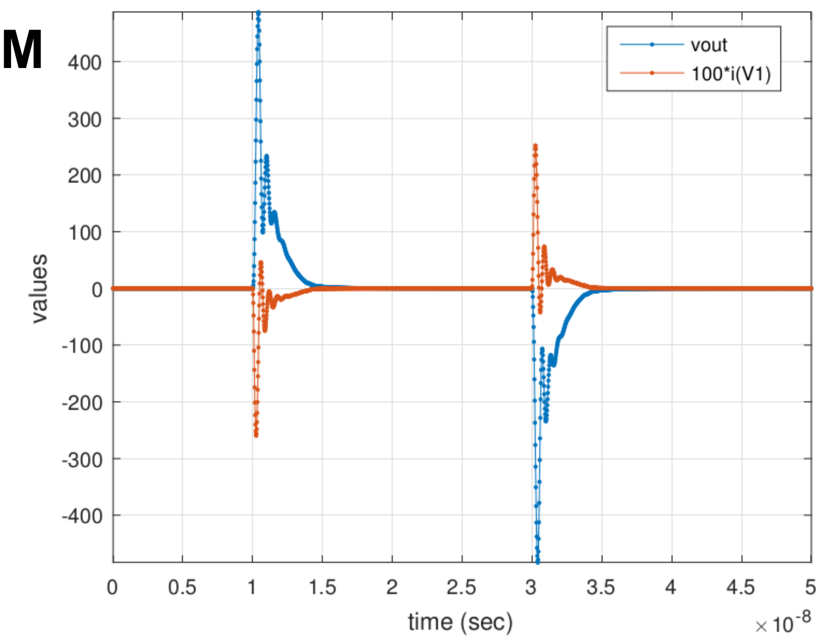


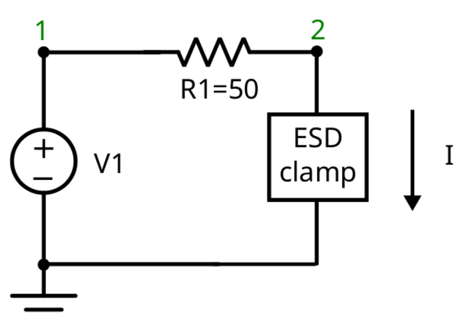
ESD Snapback Model

MM

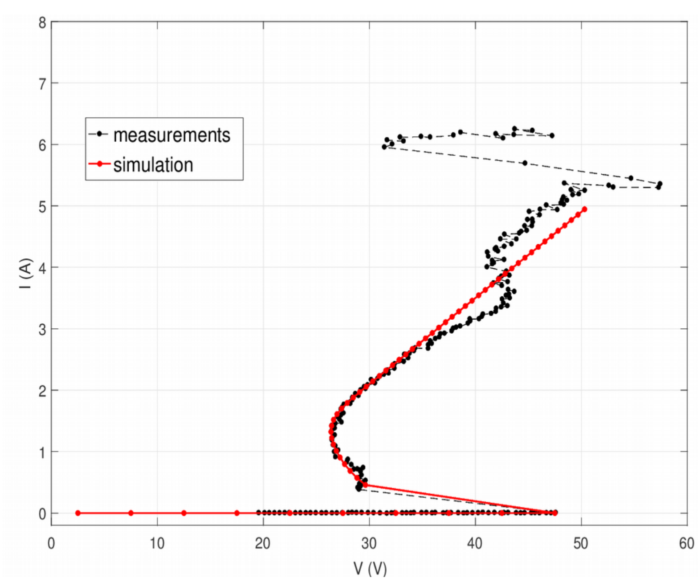


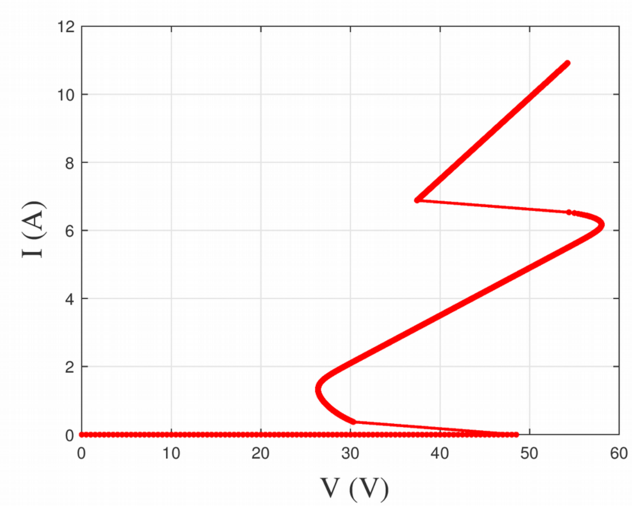
CDM



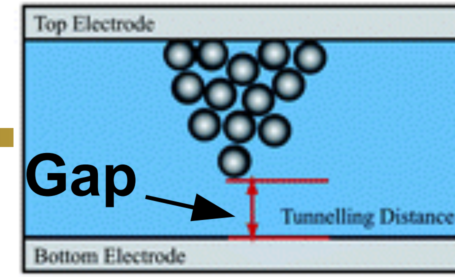


simple TLP equivalent circuit





RRAM Model



Template:

$$\mathbf{ipn} = f_1\left(\mathbf{vpn},\ \mathbf{s}\right)$$

$$\frac{d}{dt}\mathbf{s} = f_2\left(\mathbf{vpn},\ \mathbf{s}\right)$$

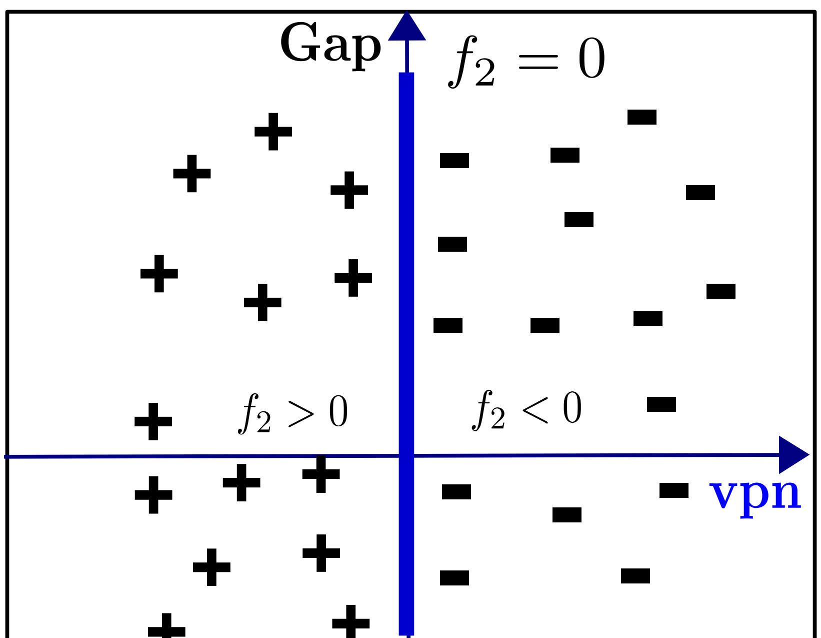
RRAM:

$$f_1\left(\mathbf{vpn},\ \mathbf{Gap}\right) = I_0 \cdot e^{-\mathbf{Gap}/g0} \cdot \sinh(\mathbf{vpn}/V_0)$$

$$f_2\left(\mathbf{vpn},\ \mathbf{Gap}\right) = -v_0 \cdot \exp(-\frac{E_a}{V_T}) \cdot \sinh(\frac{\mathbf{vpn} \cdot \gamma \cdot a_0}{t_{ox} \cdot V_T})$$

Jiang, Z., Wong, H. (2014). Stanford University Resistive-Switching Random Access Memory (RRAM) Verilog-A Model. nanoHUB.

$$\mathbf{minGap} \leq \mathbf{Gap} \leq \mathbf{maxGap}$$



```
if gap < minGap
      gap = minGap;
```

hybrid model

RRAM Model

Template:

$$\mathbf{ipn} = f_1\left(\mathbf{vpn},\ \mathbf{s}\right)$$

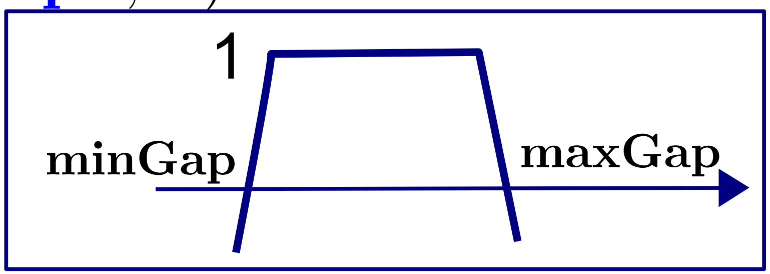
$$\frac{d}{dt}\mathbf{s} = f_2\left(\mathbf{vpn},\ \mathbf{s}\right)$$

RRAM:

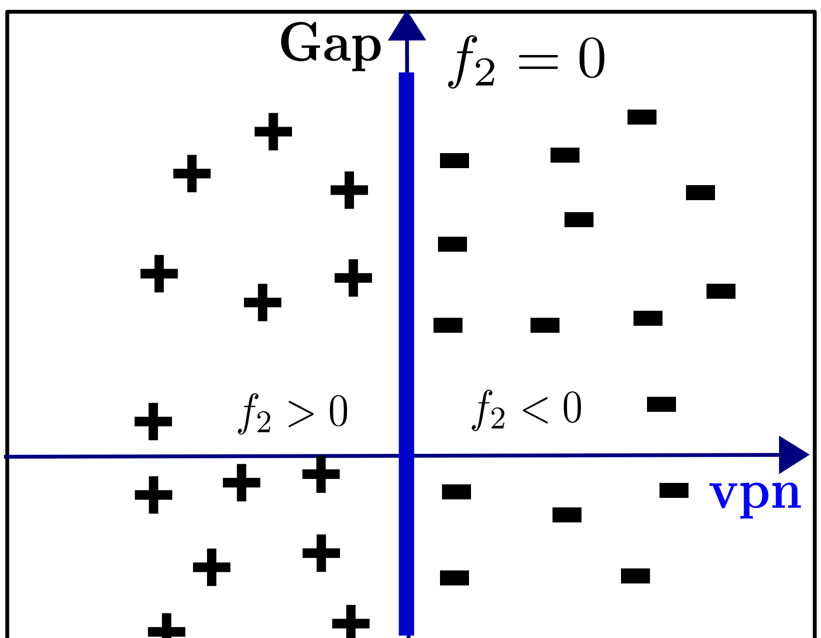
$$f_1\left(\mathbf{vpn},\ \mathbf{Gap}\right) = I_0 \cdot e^{-\mathbf{Gap}/g0} \cdot \sinh(\mathbf{vpn}/V_0)$$

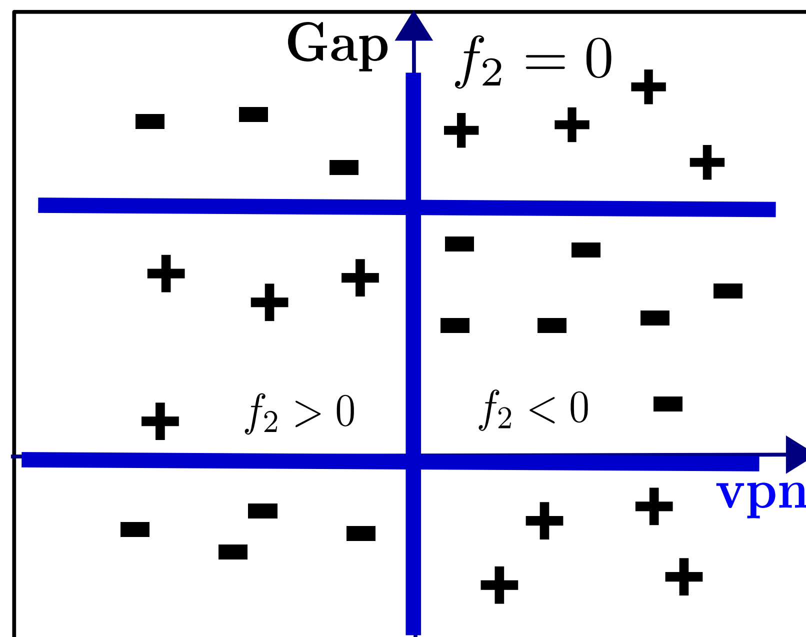
$$f_2\left(\mathbf{vpn},\ \mathbf{Gap}\right) = -v_0 \cdot \exp(-\frac{E_a}{V_T}) \cdot \sinh(\frac{\mathbf{vpn} \cdot \gamma \cdot a_0}{t_{ox} \cdot V_T})$$

$$\times F_{window}(\mathbf{Gap})$$

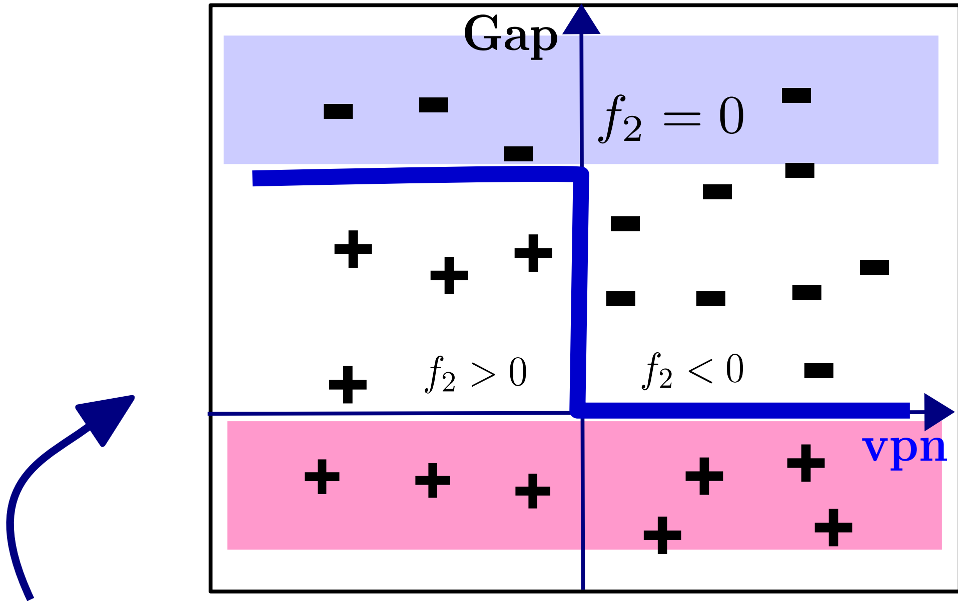


Biolek, Jogelkar, Prodromakis, UMich, TEAM/VTEAM, Yakopcic, etc.



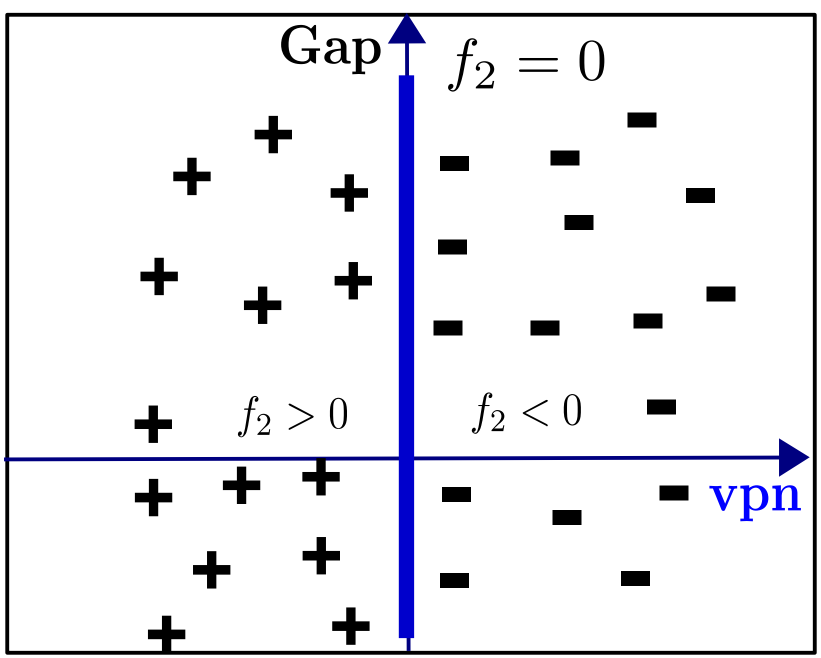


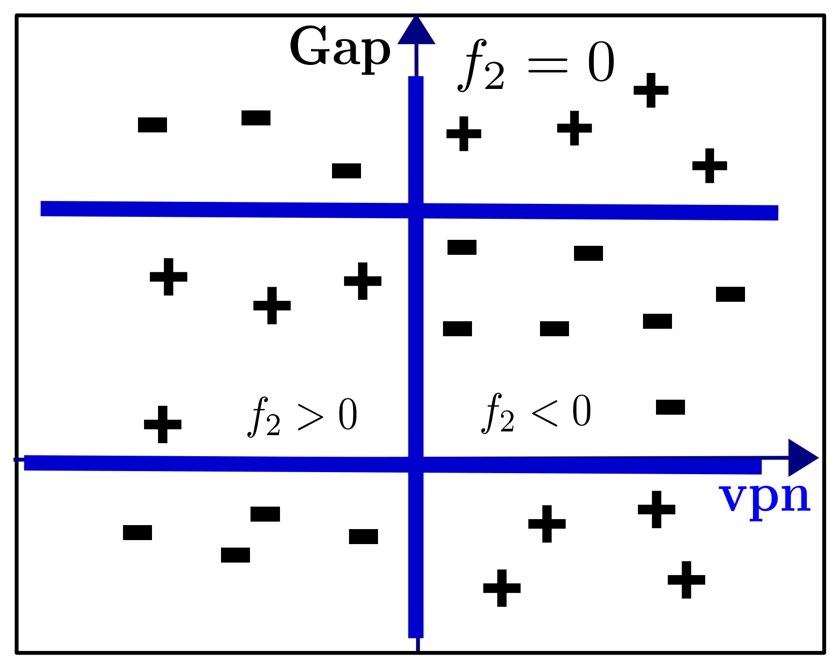
RRAM Model



clipping functions

Analogy: MEMS switch
Zener diode voltage regulator





Memristor Models

$$\frac{d}{dt}\mathbf{s} = f_2\left(\mathbf{vpn},\ \mathbf{s}\right)$$

$$\mathbf{ipn} = f_1\left(\mathbf{vpn},\ \mathbf{s}\right)$$

Available f2:

1. linear ion drift

$$f_2 = \mu_v \cdot R_{on} \cdot f_1(\mathbf{vpn},\ s)$$

2. nonlinear ion drift

$$f_2 = a \cdot \mathbf{vpn}^m$$

3. Simmons tunnelling barrier

$$f_2 = \begin{cases} c_{off} \cdot \sinh(\frac{i}{i_{off}}) \cdot \exp(-\exp(\frac{s-a_{off}}{w_c} - \frac{i}{b}) - \frac{s}{w_c}), & \text{if } i \geq 0 \\ c_{on} \cdot \sinh(\frac{i}{i_{on}}) \cdot \exp(-\exp(\frac{a_{on}-s}{w_c} + \frac{i}{b}) - \frac{s}{w_c}), & \text{otherwise,} \end{cases}$$

4. TEAM model

5. Yakopcic model

6. Stanford/ASU

$$f_2 = -v_0 \cdot \exp(-\frac{E_a}{V_T}) \cdot \sinh(\frac{\mathbf{vpn} \cdot \gamma \cdot a_0}{t_{ox} \cdot V_T})$$

Available f1:

1. $$f_1 = (R_{on} \cdot s + R_{off} \cdot (1-s))^{-1} \cdot \mathbf{vpn}$$

2. $$f_1 = \frac{1}{R_{on}} \cdot e^{-\lambda \cdot (1-s)} \cdot \mathbf{vpn}$$

3. $$f_1 = s^n \cdot \beta \cdot \sinh(\alpha \cdot \mathbf{vpn}) + \chi \cdot (\exp(\gamma \cdot) - 1)$$

4. $$\mathrm{f}_1 = \begin{cases} A_1 \cdot s \cdot \sinh(B \cdot \mathbf{vpn}), & \text{if } \mathbf{vpn} \geq \mathbf{0} \\ A_2 \cdot s \cdot \sinh(B \cdot \mathbf{vpn}), & \text{otherwise.} \end{cases}$$

5. $$f_1 = I_0 \cdot e^{-\mathbf{Gap}/g0} \cdot \sinh(\mathbf{vpn}/V_0)$$
$$\mathbf{Gap} = s \cdot minGap + (1-s) \cdot maxGap.$$

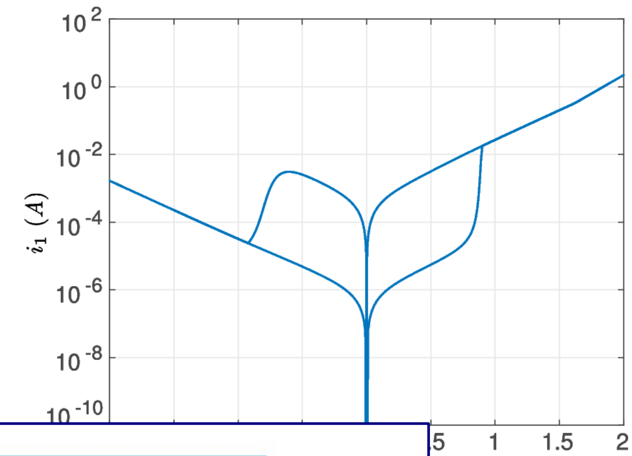
- **set up boundary**
- **fix f2 flat regions**
- **smooth, safe funcs, scaling, etc.**

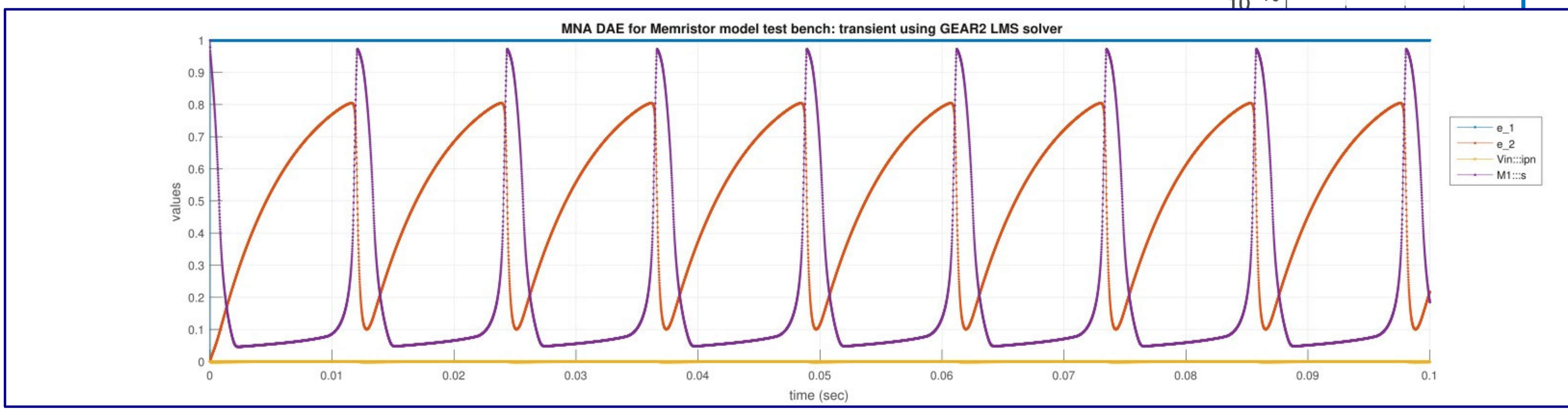
Wang/Roychowdhury. "Well-Posed Models of Memristive Devices." arXiv preprint (2016).

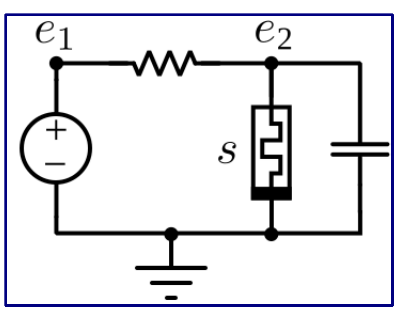
Memristor Models

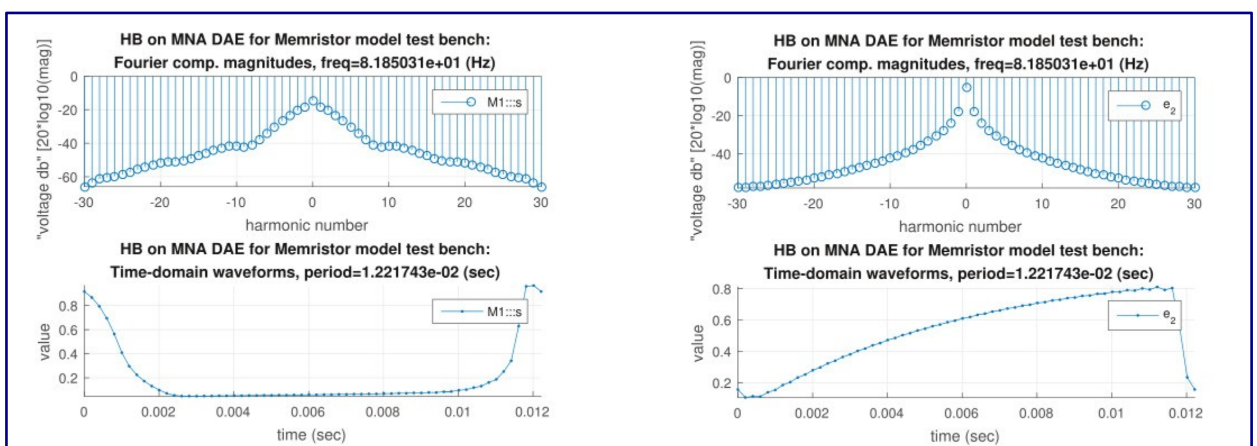
A collection of models:

- all smooth, all well posed
- not just RRAM, but general memristive devices
- not just bipolar, but unipolar
- not just DC, AC, TRAN, but homotopy, PSS, ...









PSS using HB

Good Compact Models

- Well-posedness:
  - finite and unique outputs
  - continuous and smooth
  - input range
  - physics, DAE, tests, Verilog-A …
- Good Verilog-A practices

  Geoffrey Coram, "How to (and how not to) write a compact model in Verilog-A"

  Colin McAndrew et al, "Best Practices for Compact Modeling in Verilog-A"

  A.G. Mahmutoglu et al, "Well-Posed Device Models for Electrical Circuit Simulation"
- Case study with hysteretic devices
  - ESD snapback
  - RRAM/memristors