# Simulation Model of the Integrated Hall Element Implemented in Verilog-A

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# Damjan Berčan

**Damjan Berčan** received a master's degree in electrical engineering from the University of Ljubljana in 2016. Currently he is a young researcher and assistant at the faculty of Electrical Engineering. His research interests are focused on the development of advanced magnetic microsystems based on Hall effect elements.

# Introduction

**History**

- 1879 discovery of the Hall effect (Edwin Hall),
- 1960 – 1970 first integrated circuit using the Hall effect element.

**Hall effect in semiconductor**

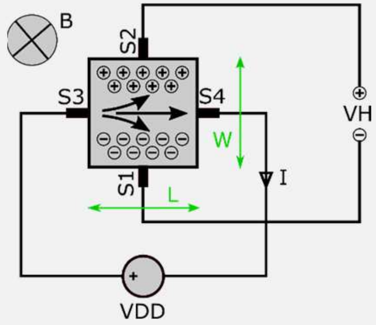
- Electric current $I$ (S3, S4) is exposed to the magnetic field $\vec{B}$.
- Lorentz force $\vec{F}$ acts upon electrons and holes.
- Hall voltage $V_H$ appears between (S1, S2).

**Key parameters**

- Sensitivity,
- power consumption,
- temperature coefficient (nonlinear),
- linearity,
- noise (thermal, 1/f),
- offset voltage.

$$\vec{F} = q\vec{E} + q\vec{v} \times q\vec{B}$$

$$V_H = \frac{IB_\perp}{qnt}$$



# Motivation

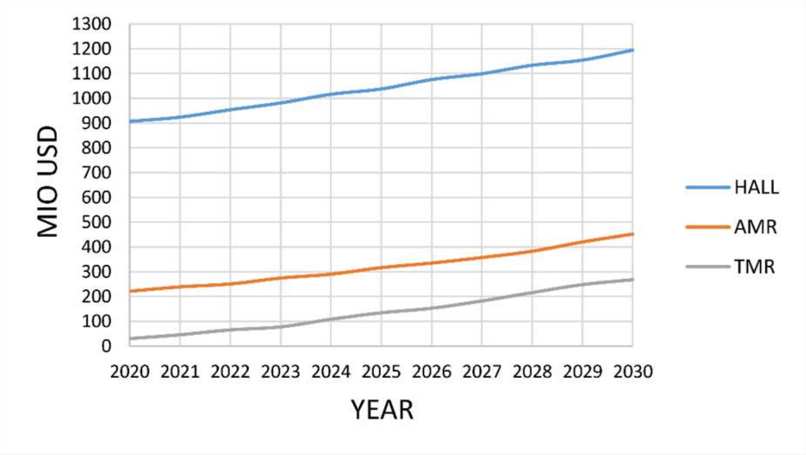
**Why use the Hall effect sensor?**

- Contactless measurement
  - current, power, energy, position, distance, angle, speed, Earth's magnetic field
- CMOS compatible,
- Long life,
- Wide temperature range (from -40 °C to 125 °C),
- Cheaper (compare to the e.g. AMR and TMR).

**Sources of the magnetic fields: e.g. electric current and ferromagnetic materials**

**Market for magnetic sensors**

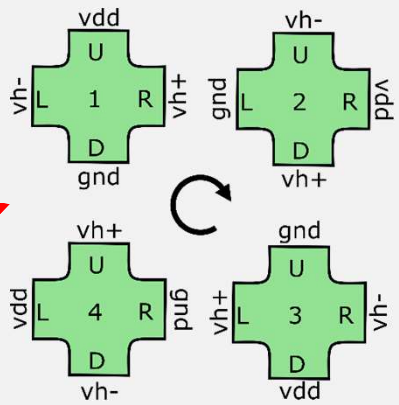
- The market for silicon Hall effect sensors will exceed $1,2 billion in 2030.

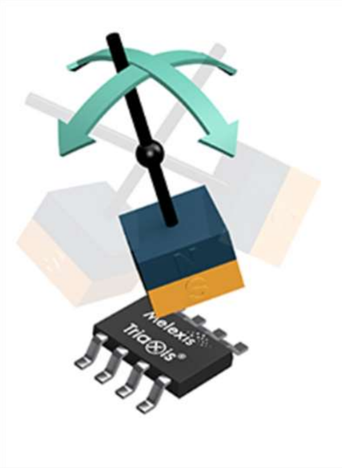


# State of the Art

## State of the art in CMOS Hall Magnetic Sensors

- Sensitivity improvement,
- offset voltage reduction,
  - without current spinning technique (mV)
  - with current spinning technique (μV)
- increase of the Hall element and signal conditioner bandwidth,
- 3D Hall element,
- minimizing power consumption,
- minimizing Hall element,
- simulation model improvement.




*Melexis – Triaxis sensors

*https://www.melexis.com/en/insights/knowhow/triaxis-position-sensing-solution

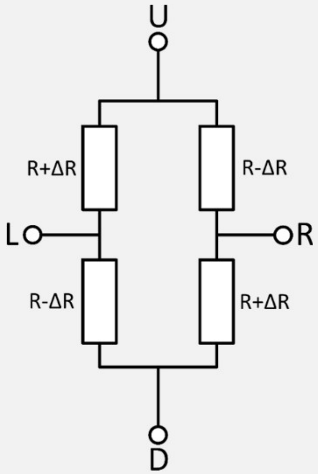
# Simulation Model

**Simulation model should take into account:**

- Offset voltage (temperature depended, random function),
- external and internal magnetic fields,
- influence of the integrated coil heating
- temperature variation of the sensitivity (nonlinear function),
- mechanical stress.

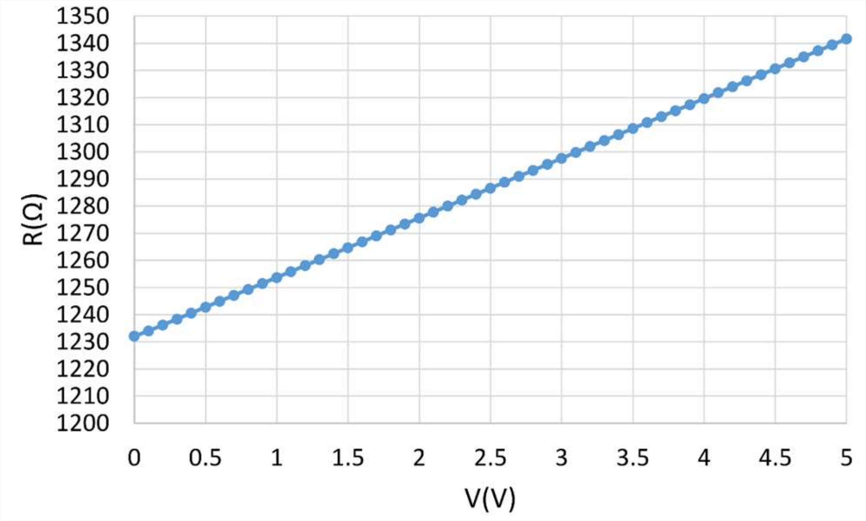
**Basic model – Resistor bridge connection**

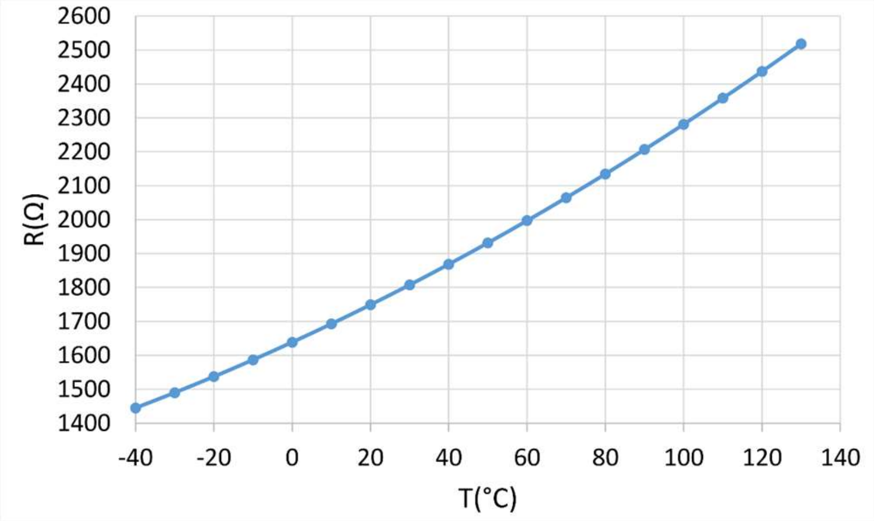
- Consist of four N-well resistors representing N-well Hall element resistance.



# Simulation Results

**Simulation results of the N-Well structure (resistor)**

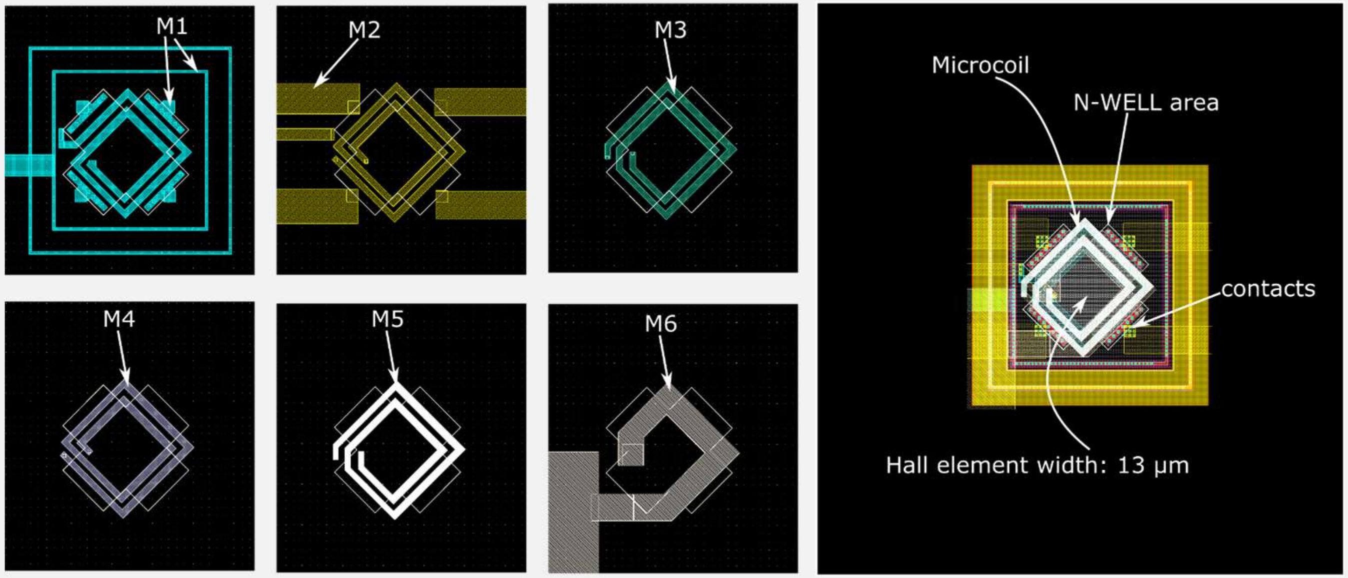



- 8,9 % (from 0 V to 5 V)
- 43 % (from -40 °C to 125 °C)

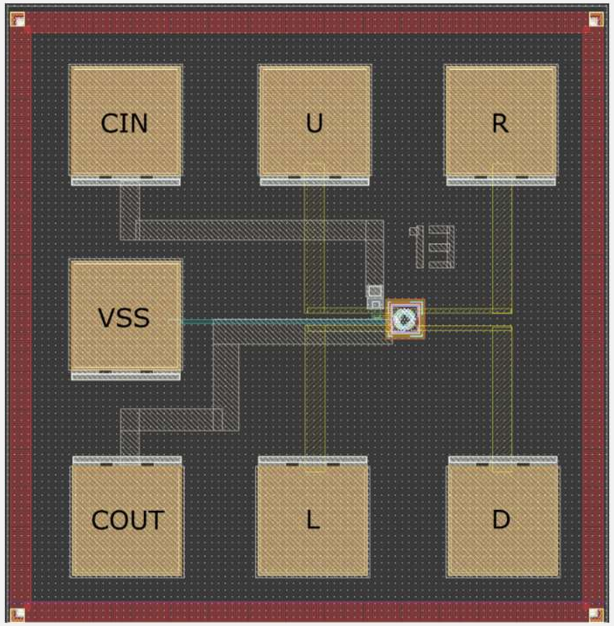
# Cross-Shaped Hall Element with Microcoil

**The complete cross-shaped Hall element with microcoil (0.18 μm BCD technology) – layout**



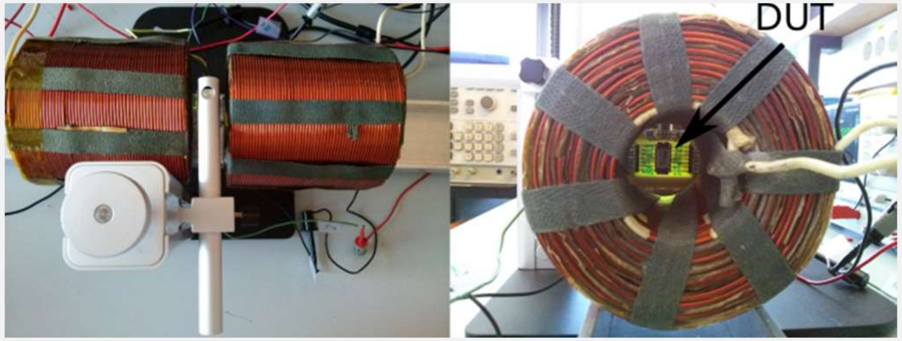
# Measurement Results

**Microphotography of the integrated Hall element**




**Sensitivity measurement results to the applied external magnetic field**

- B = 34 mT (340 G)
- $S_I$ = 50 V/AT



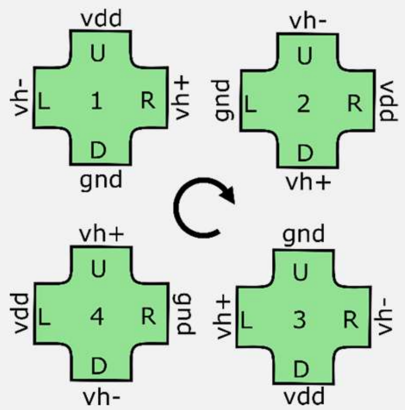
# Measurement Results

**Offset voltage measurement results at the constant voltage source and the constant current source for N=20 samples.**

| | Voltage Biased | | Current Biased | |
|---|---|---|---|---|
| T (°C) | Vo (mV) | Ib (mA) | Vo (mV) | Ib (mA) |
| -40 | -0.324 | 2.000 | -0.324 | 2 |
| -20 | -0.445 | 1.918 | -0.465 | 2 |
| 0 | -0.529 | 1.828 | -0.588 | 2 |
| 20 | -0.656 | 1.733 | -0.768 | 2 |
| 40 | -0.793 | 1.636 | -1.005 | 2 |
| 60 | -0.926 | 1.542 | -1.247 | 2 |
| 80 | -1.050 | 1.445 | -1.531 | 2 |
| 100 | -1.168 | 1.360 | -1.838 | 2 |
| 120 | -1.272 | 1.280 | -2.167 | 2 |

$$V_o = 2 \cdot 10^{-8}x^3 - 2 \cdot 10^{-5}x^2 - 0.0042x - 0.297$$

- Large offset voltage (mV).
- Current spinning technique should be used to reduced it to (µV).



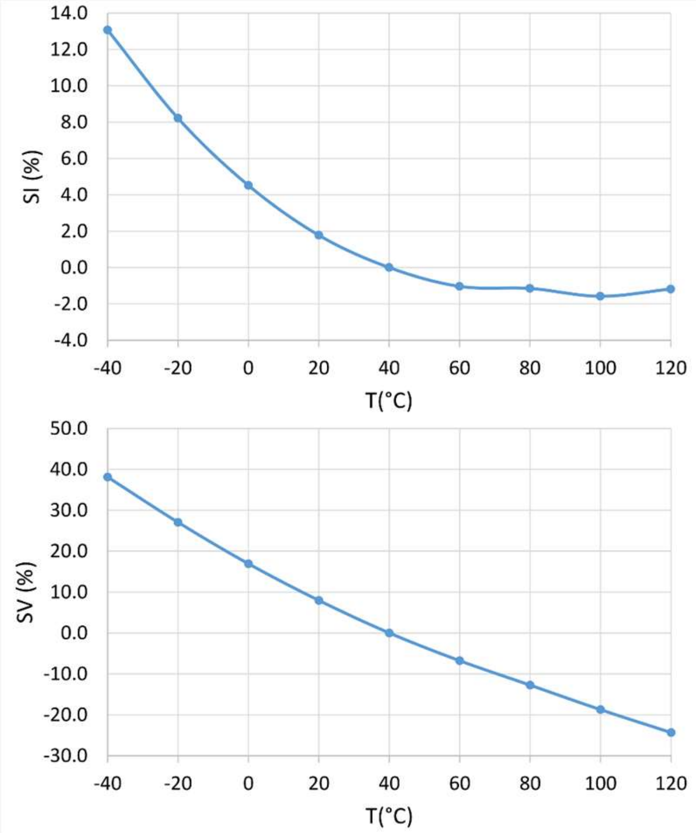

| N | Vo (µV) |
|---|---|
| 20 | 11.5 |

# Measurement Results

**Sensitivity measurement results to the applied external magnetic field for N=20 samples**

| T (°C) | SV (V/VT) | SI (V/AT) |
|---|---|---|
| | | |
| -40 | 0,034 | 54,2 |
| -20 | 0,032 | 51,9 |
| 0 | 0,029 | 50,1 |
| 20 | 0,027 | 48,8 |
| 40 | 0,025 | 48,0 |
| 60 | 0,023 | 47,5 |
| 80 | 0,022 | 47,4 |
| 100 | 0,020 | 47,2 |
| 120 | 0,019 | 47,4 |

$$\delta_o = 8.83 \cdot 10^{-6} x^2 - 1.50 \cdot 10^{-3} x + 0.0035$$



# Measurement Results

**Sensitivity measurement results to the applied internal magnetic field for N=20 samples.**

@ 1 mA - Hall element bias current

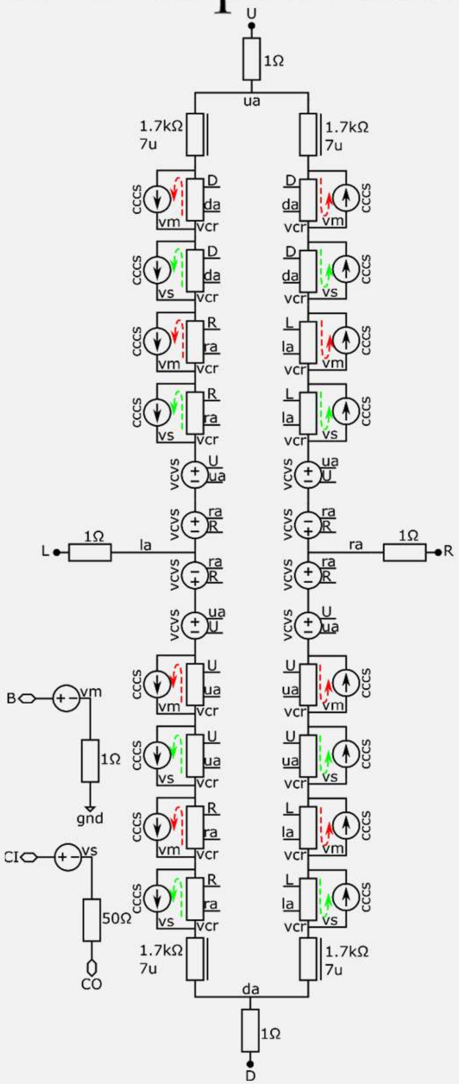
@ 1 mA - Microcoil current

- Integrated microcoil generates 0.52 mT or 5.2 G.

| N | R (Ω) | SI (V/AA) |
|---|---|---|
| | | |
| 20 | 57.4 | 26.9 |

- The integrated microcoil is used for self-calibration of the Hall element and automatic gain control.
- The integrated microcoil is also used for production testing of the magnetic microsystem etc.

# The Complex Electrical Schematic of the Six Terminal Hall Element Simulation Model




- Each voltage controlled resistor (VCR) and current controlled current source (CCCS) form a current loop.
- VCRs only work for positive values (positive resistance), therefore two current loops are added to each branch.
- The value of the four VCRs when the external magnetic field is applied is determined by the voltage drop across the sensing resistor. The others value is 0.
- The current in each loop depends on the CCCS controlled by the current flow through the resistor connected between contacts *B* and *gnd* or *CI* and *CO*.

# Development of the Verilog–A Based Hall Element Model

## CCCS description in Verilog-A

```
// VerilogA, CCCS
‘include "constants.vams"
‘include "disciplines.vams"
        module cccs (pi, ni, p, n);
        inout p, n, pi, ni;
        electrical pi, ni, p, n;
        parameter real gain=1;
        parameter real rm=1;
        branch (p, n) out;
        branch (pi, ni) in;
        parameter real pt=($temperature-273.15);
        parameter real ksen3=0;
        parameter real ksen2=0;
        parameter real ksen1=0;
        parameter real nsen=0;
        parameter real sen=0;
        real ksen=0;
analog begin
        if (sen==1) begin
ksen=(ksen3*(pt)*(pt)*(pt)+ksen2*(pt)*(pt)+ksen1*(pt) + nsen);end
        else if (sen!=1) begin ksen=0; end
        I(out)<+((1+ksen)*(gain*V(in)))/rm; end
endmodule
```

- The value of the current *I(out)* depends on the input voltage applied to port *B*, which represents external magnetic field or on the input voltage applied to terminal *CI*, which represents internal magnetic field.
- The absolute value of sensitivity to the external or internal magnetic field can be adjusted by the *gain* parameter.
- The polynomial *ksen* with the corresponding coefficients represents the relative error $\delta$, which is used to adjust the sensitivity according to the temperature parameter *pt.*

# Development of the Verilog–A Based Hall Element Model

## VCVS description in Verilog-A

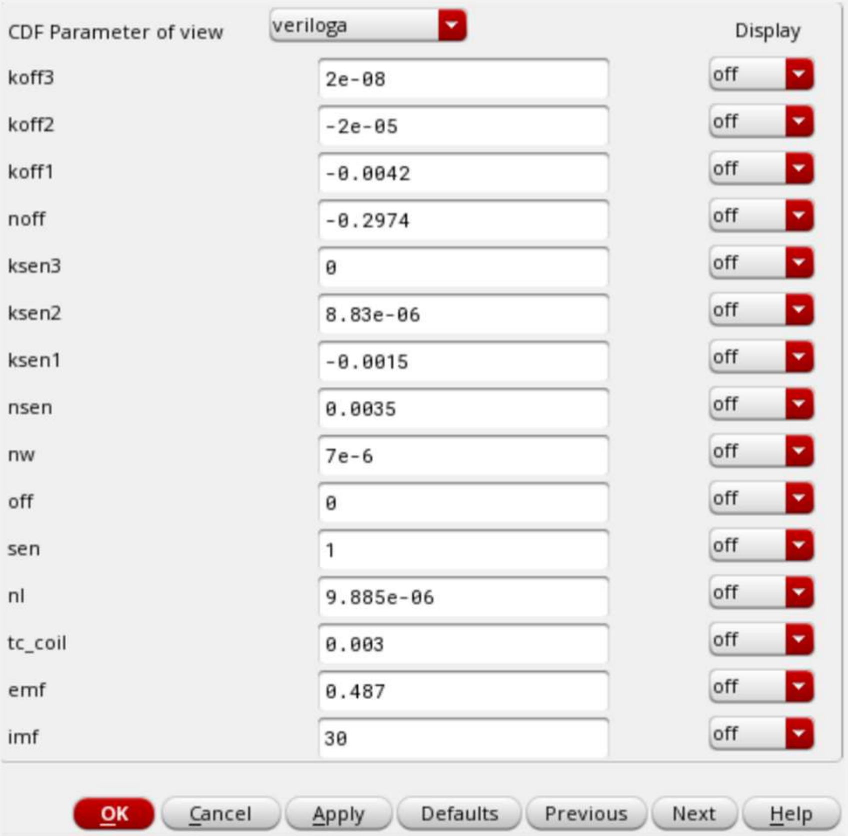
```
// VerilogA, VCVS
module vcvs (p2, n2, p1, n1);
inout p2, n2, p1, n1;
electrical p2, n2, p1, n1;
parameter real pt=($temperature-273.15);
parameter real koff3=0;
parameter real koff2=0;
parameter real koff1=0;
parameter real noff=0;
parameter real off=0;
real vctrl;
real koff;
analog begin
vctrl=V(p2,n2)/2;
if (off==1) begin
koff=(noff+koff3*(pt)*(pt)*(pt)+koff2*(pt)*(pt)+koff1*(pt)); end
else if (off!=1) begin koff=0; end
V(p1,n1)<+vctrl*abs(koff);
end
endmodule
```

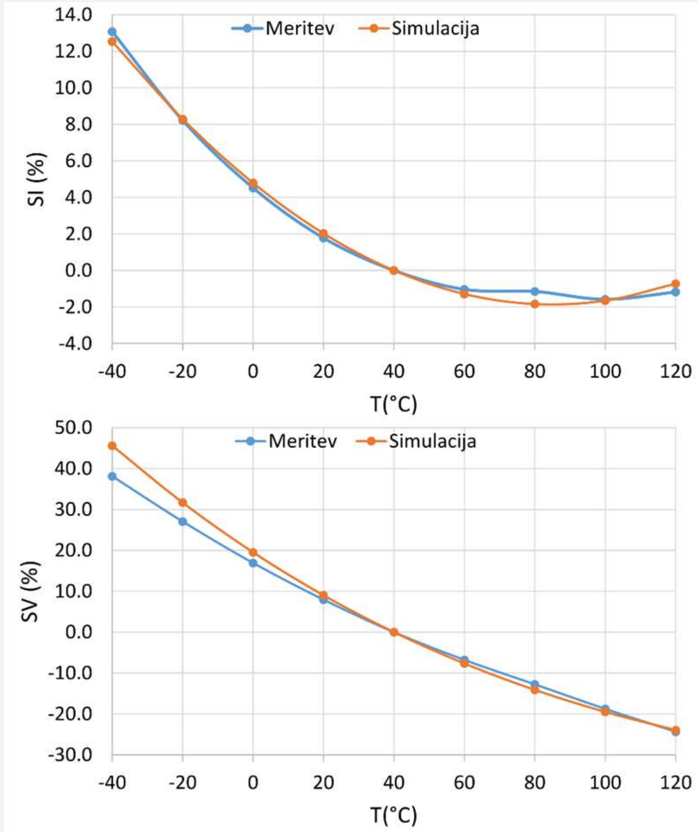
- The voltage controlled voltage source depends on the voltage drop across the current sensing resistor, which represents the bias current of the Hall element.

- To simulate the offset voltage and its temperature dependency the polynomial *koeff* with the corresponding coefficients is added.

- The offset voltage can be switched *on* or *off* by setting the *off* parameter to *one* or *zero* respectively.

# Verification



# Conclusions

- A development of the Hall element simulation model written in Verilog-A was presented.
- Some solutions for characterizing the Hall element in case, the technological data are not fully available are introduced.
- All the Hall element parameters can be set according to the measurement results.
- The simulation model takes into account the internal magnetic field, the external magnetic field, offset voltage, the temperature dependence of the sensitivity of the Hall element and its offset voltage, and the packaging stress.

# Simulation Model of the Integrated Hall Element Implemented in Verilog-A

## Thank you!

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