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OPTIMIZATION OF TRANSMISSION LINE MEASUREMENT (TLM) STRUCTURES FOR CONTACT RESISTIVITY DETERMINATION

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Outline

Motivation

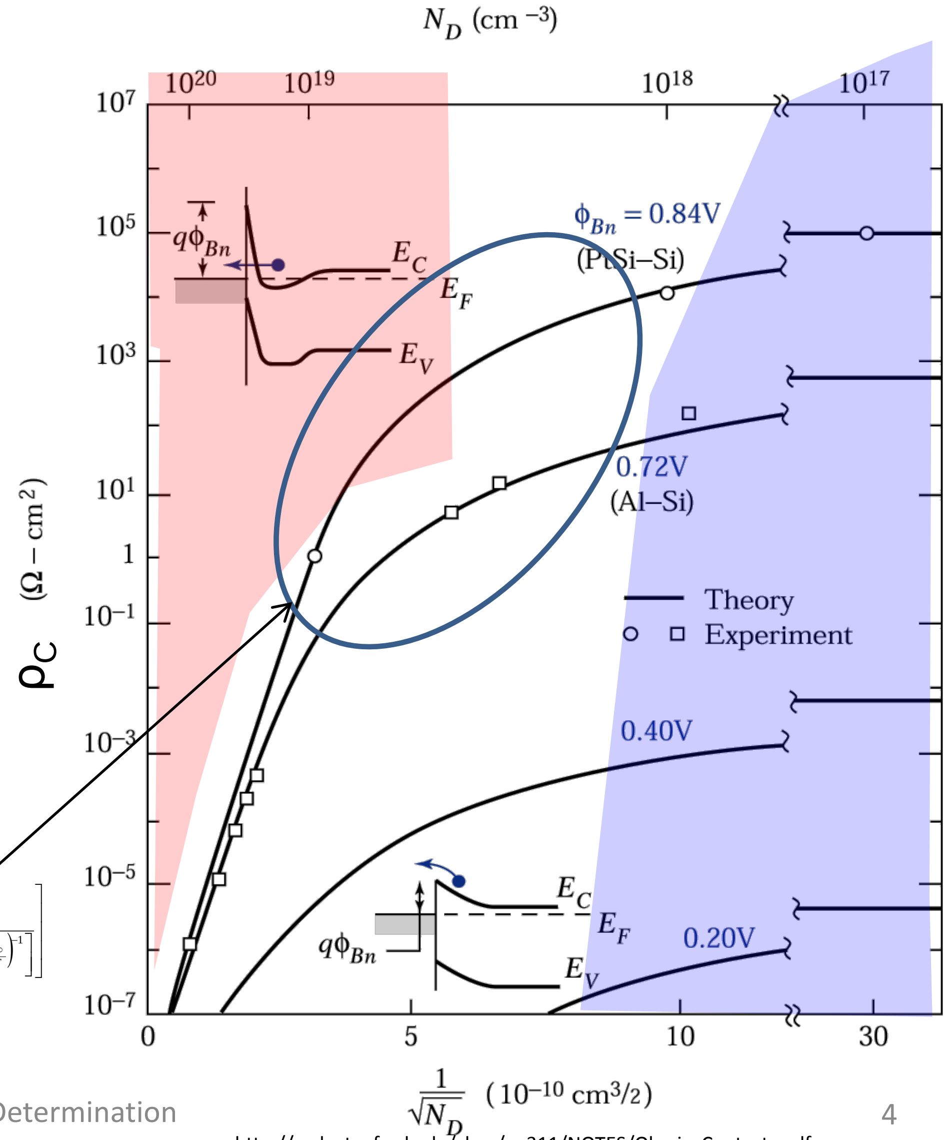
- Low Resistance ohmic contacts are of extreme importance to semiconductor devices.
- Transmission Line Measurement (TLM) structures are most commonly used to determine specific contact resistivity (ρ_c) for Integrated Circuits (IC's) and Silicon Photovoltaics (PV).
- Accurate determination of ρ_c is essential for characterizing semiconductor devices of different dimensions.
- Inconsistencies have been observed for ρ_c determination in literature between IC and PV devices as ρ_c determination may depend on TLM dimensions.
- TLM test geometries therefore need to be optimized for ρ_c in order to minimize error.

What is Specific Contact Resistivity (ρ_c)?

- It is a figure-of-merit for ohmic contacts
  - Defined as $\rho_c \equiv \left(\frac{\partial J}{\partial V}\right)^{-1}\Bigg|_{V=0}$ $\Omega - cm^2$
- Observe that
  - For $N_D \geq 10^{19}\text{cm}^{-3}$, ρ_C is dominated by the tunneling process and decreases rapidly with increased doping.
  - For $N_D \leq 10^{17}\text{cm}^{-3}$, the current is due to thermionic emission, and ρ_C is essentially independent of doping.
  - For in between: thermionic + tunneling

$$\rho_C \approx \exp\left[\frac{\phi_B}{\sqrt{N_D}\left[\coth\left(\frac{E_\infty}{kT}\right)^{-1}\right]}\right]$$

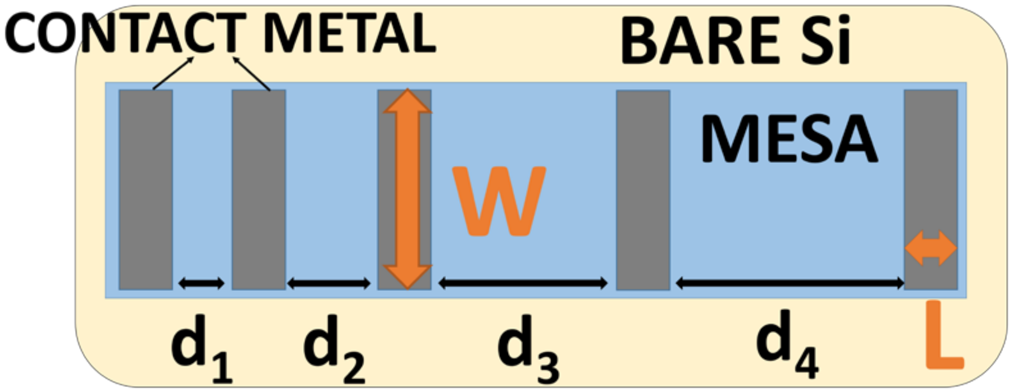
$$E_\infty = \left(\frac{q\hbar}{2}\right)\left(\frac{N_D}{m^*\varepsilon}\right)^{1/2}$$

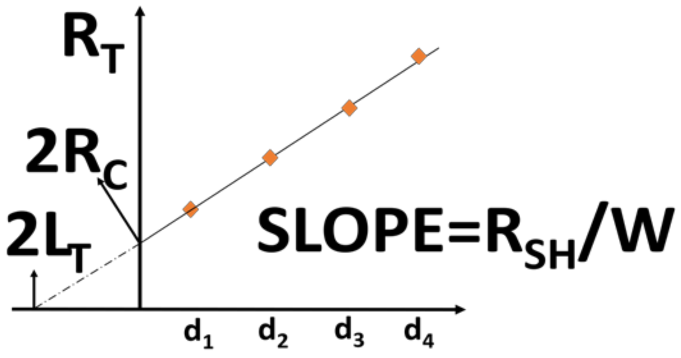


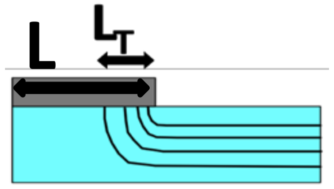
http://web.stanford.edu/class/ee311/NOTES/Ohmic_Contacts.pdf

TLM Measurement

- Contacts with length(L) and width(W) are fabricated with varying spacings (d) on diffused MESA regions.
- I-V measurements are carried out on the diffused resistors on each of the different spacings.
- Resistance values obtained from each measurement are plotted with respect to the spacing.
- The plot obtained is used to extract values of sheet resistance(R_{SH}), contact resistance(R_c), transfer length(L_T)
- Transfer length L_T is the average distance and electron or hole travels before it flows up into a contact







http://tuttle.merc.iastate.edu/ee432/topics/metals/tlm_measurements.pdf

Specific Contact Resistivity (ρ_c) Extraction

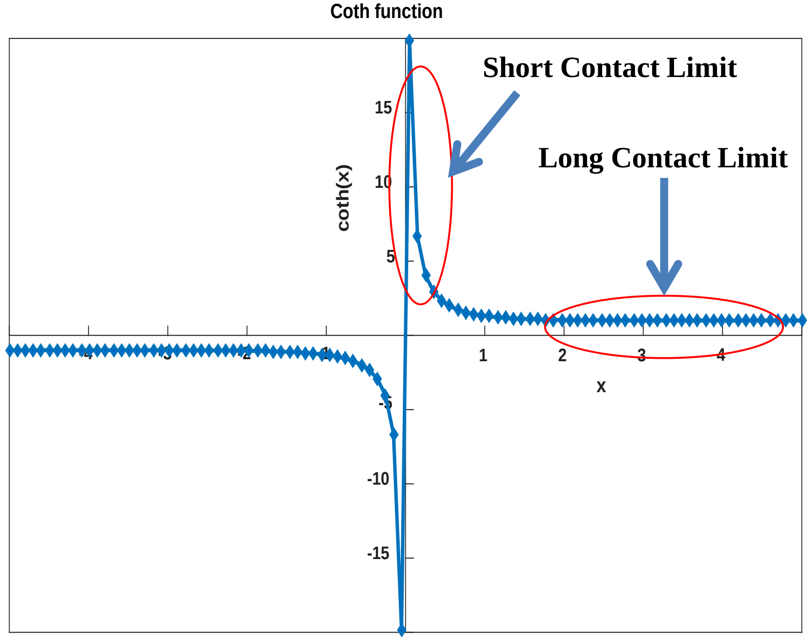
$$R_c = \frac{\sqrt{R_{SH}\rho_c}}{W}\coth\left(\frac{L_C}{L_T}\right) \Rightarrow \rho_c = \left(R_C W \tanh\left(\frac{L_C}{L_T}\right)\right)^2 * \frac{1}{R_{SH}}$$

- $L_T = \sqrt{\frac{\rho_c}{R_{SH}}}$ Transfer Length

Two limiting cases:

- (1) $L_C < 0.5L_T \rightarrow \coth\left(\frac{L_C}{L_T}\right) \approx \frac{L_T}{L_C} \Rightarrow \rho_c = R_C W L_C$
  - Short contact limit

- (2) $L_C \geq 1.5L_T \rightarrow \coth\left(\frac{L_C}{L_T}\right) \approx 1 \Rightarrow \rho_c = R_C W L_T$
  - Long contact limit



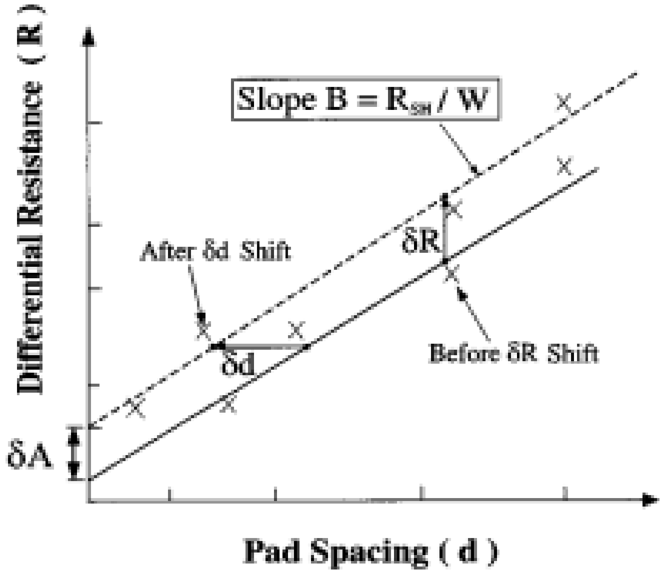
Error Analysis

- Systematic error is the consistent shift of means due to taking large amounts of data points.
- The equation for relative uncertainty due to systematic error is given by –

$$\frac{\delta\rho_C}{\rho_C} = \left(\frac{W}{\sqrt{\rho_C R_{SH}}}\right)\delta R + \left(\sqrt{\frac{R_{SH}}{\rho_C}}\right)\delta d + \left(\frac{4}{W}\right)\delta W$$

- Here δR, δd and δW are the measurement uncertainties in the resistance, pad spacing and TLM widths respectively.
- The above equation is optimized by partially differentiating and equating to zero to find an equation for the optimum width. It is given by

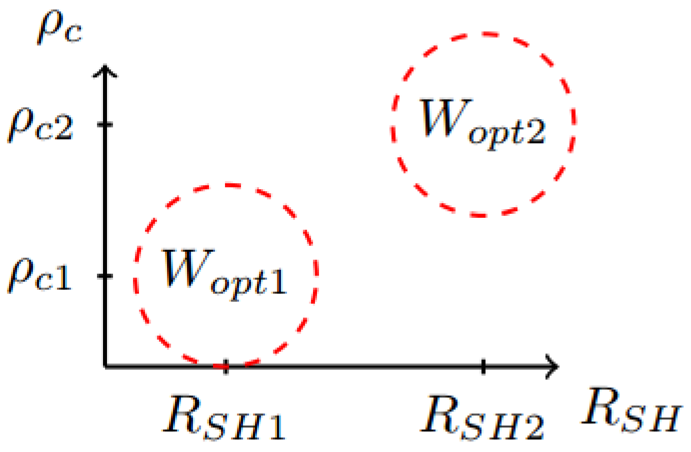
$$W_{opt} = \sqrt{4\sqrt{\rho_C R_{SH}}\left(\frac{\delta W}{\delta R}\right)}$$



Haw-Jye Ueng, D. B. Janes and K. J. Webb, "Error analysis leading to design criteria for transmission line model characterization of ohmic contacts," in *IEEE Transactions on Electron Devices*, vol. 48, no. 4, pp. 758-766, Apr 2001.

Experimental Strategy

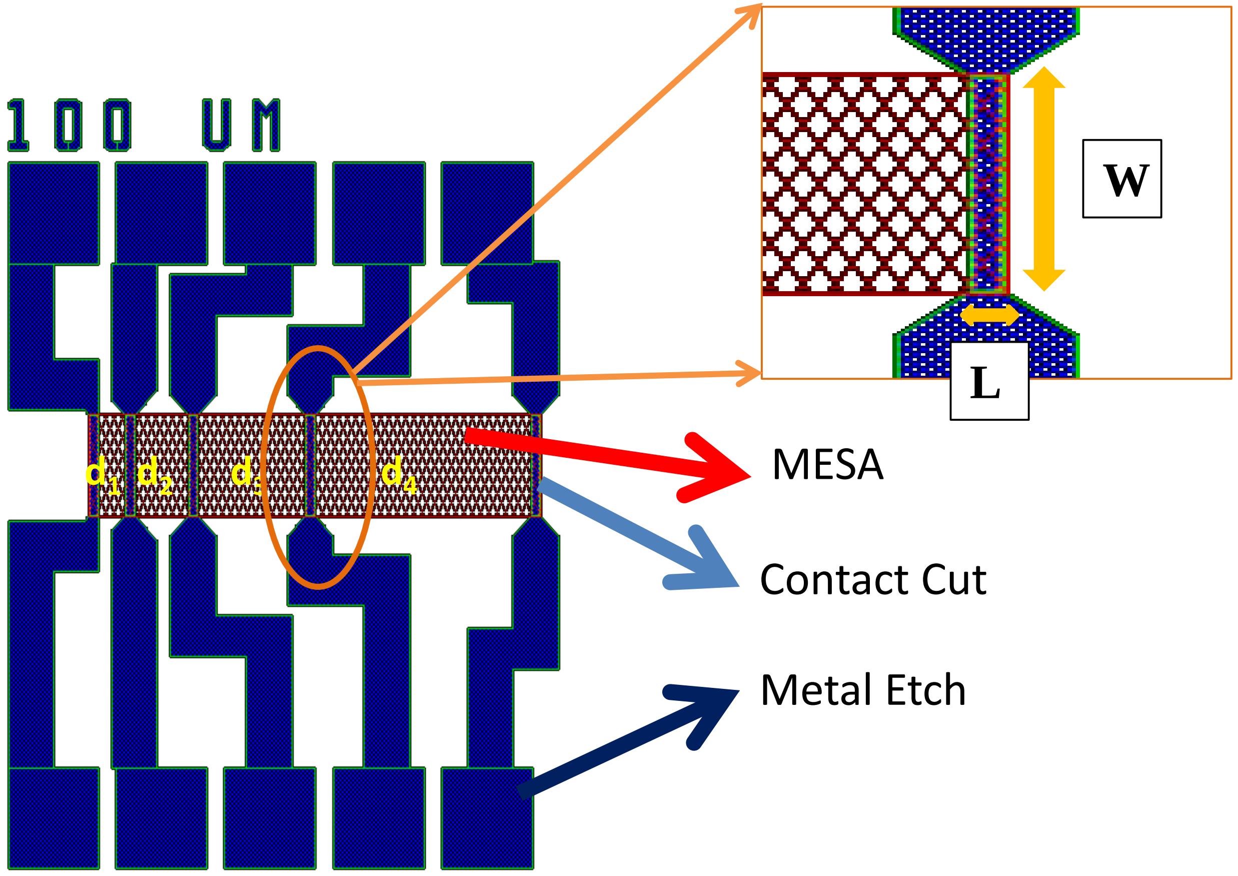
- Observed inconsistencies in literature were initially attributed to error in measurements.
- Equation for systematic error was optimized to give to obtain optimum dimension with least error in measurement.
  - Optimum width equation did not depend on TLM length (L) and transfer length (L_T)
  - Therefore, only TLM widths were varied in the experiment.
- Process was designed based on application specific R_{SH} values R_{SH1} and R_{SH2} .
- Contact schemes of Aluminum and Nickel Silicide (NiSi) were investigated.



Mask Design

- 3 level mask design for
  - MESA Definition
  - Contact Cut
  - Metal
- TLM Dimensions
  - Length(L) = 10μm
  - Width(W) = 10μm - 2000μm
  - Spacing between contacts

d_1	30μm
d_2	60μm
d_3	120μm
d_4	240μm



Process Design and Fabrication

- Application specific values of sheet resistance (R_{SH}) were chosen
  - Emitter Rs in silicon photovoltaics – 50-100 Ω/□
  - Source/Drain Rs in CMOS – 1000-3000 Ω/□
- Contacts were fabricated with Aluminum and Nickel Silicide (NiSi) metals.
- Implant parameters were used in order to obtain desired values of sheet resistances as shown

Wafer	*Dose* (cm^{-3})	*Energy (keV)*	*Target Rs (Ω/□)*	*Metal*
1	2×10^{15}	*50*	*50*	*Aluminum*
2	2×10^{15}	*50*	*50*	*NiSi*
3	9.5×10^{12}	*50*	*1500*	*Aluminum*
4	9.5×10^{12}	*50*	*1500*	*NiSi*

Process Flow

Ion Implant P31 n-type and Anneal

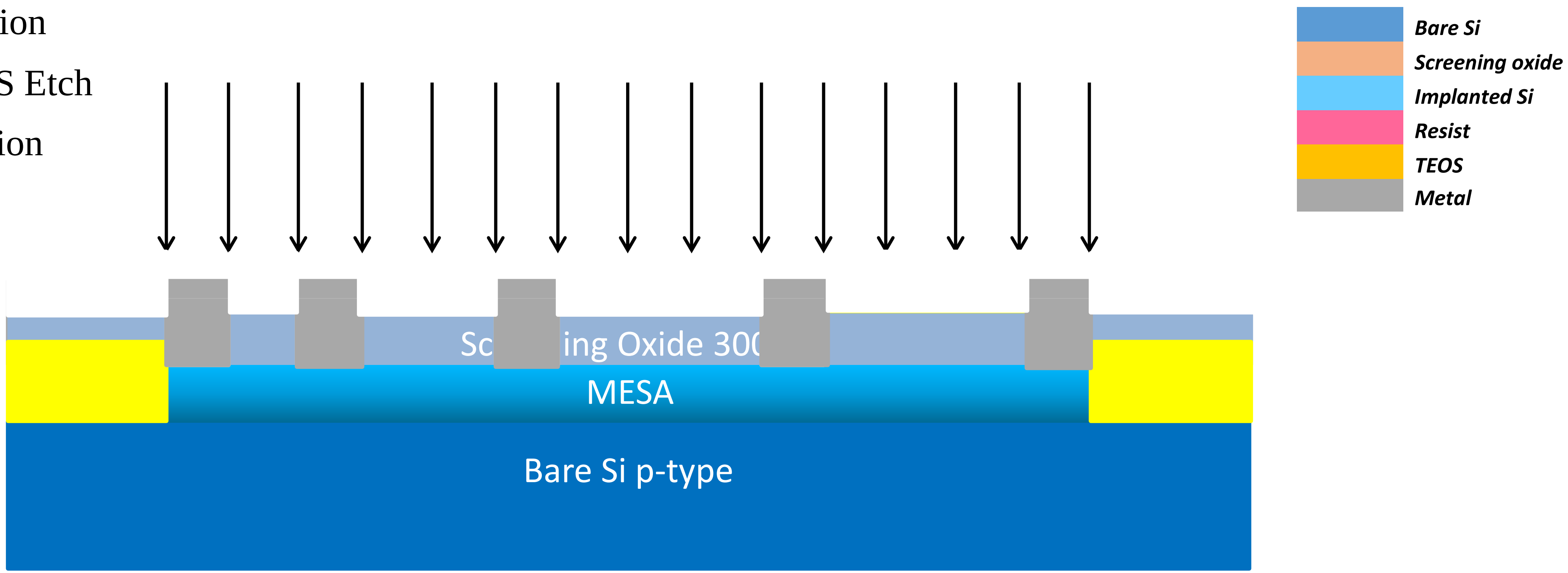
Mesa Etch

TEOS Deposition

Contact Cut TEOS Etch

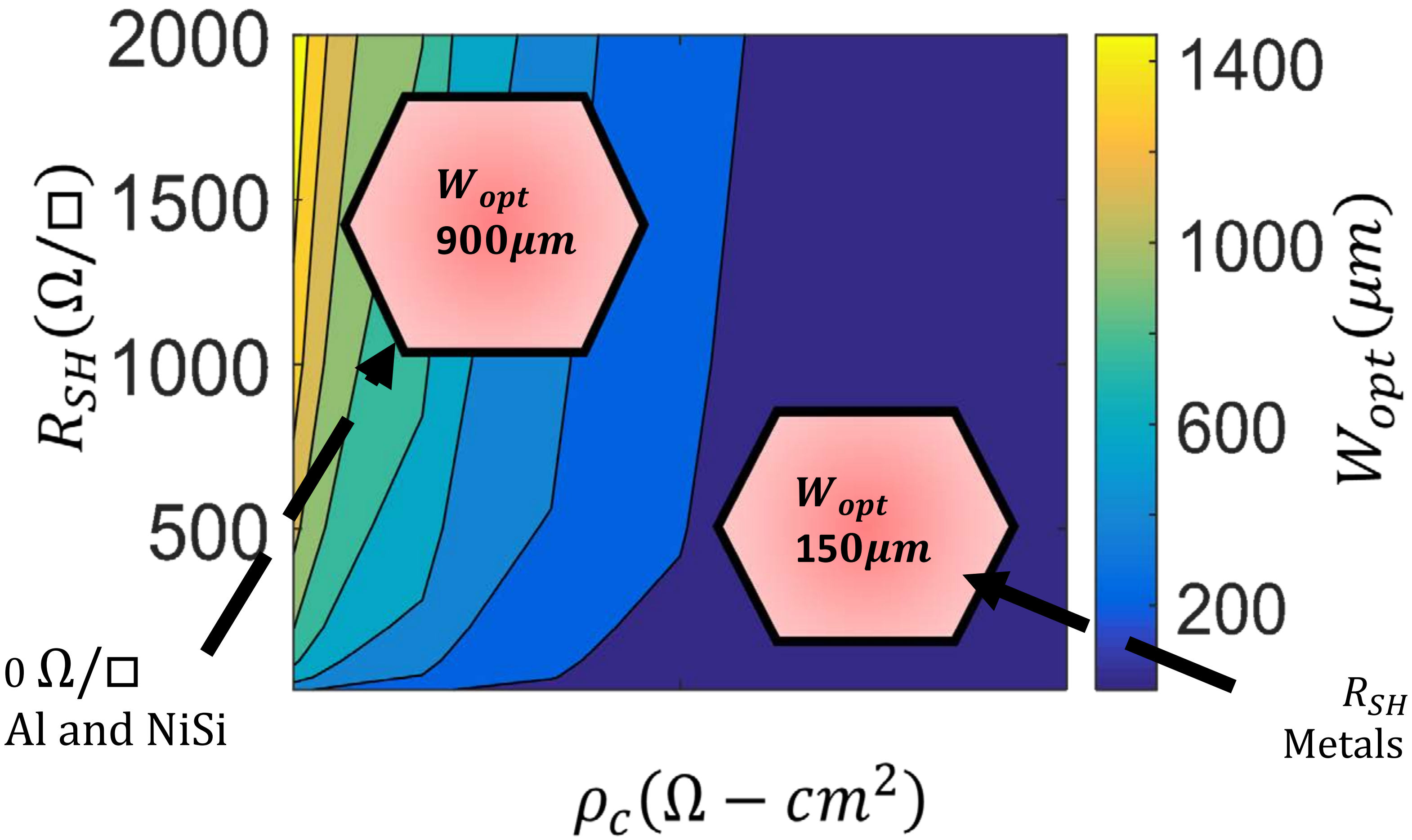
Metal Deposition

Metal Etch



Optimization Results

- Systematic error optimization gave optimum width values for application specific ρ_C and R_{SH} values.



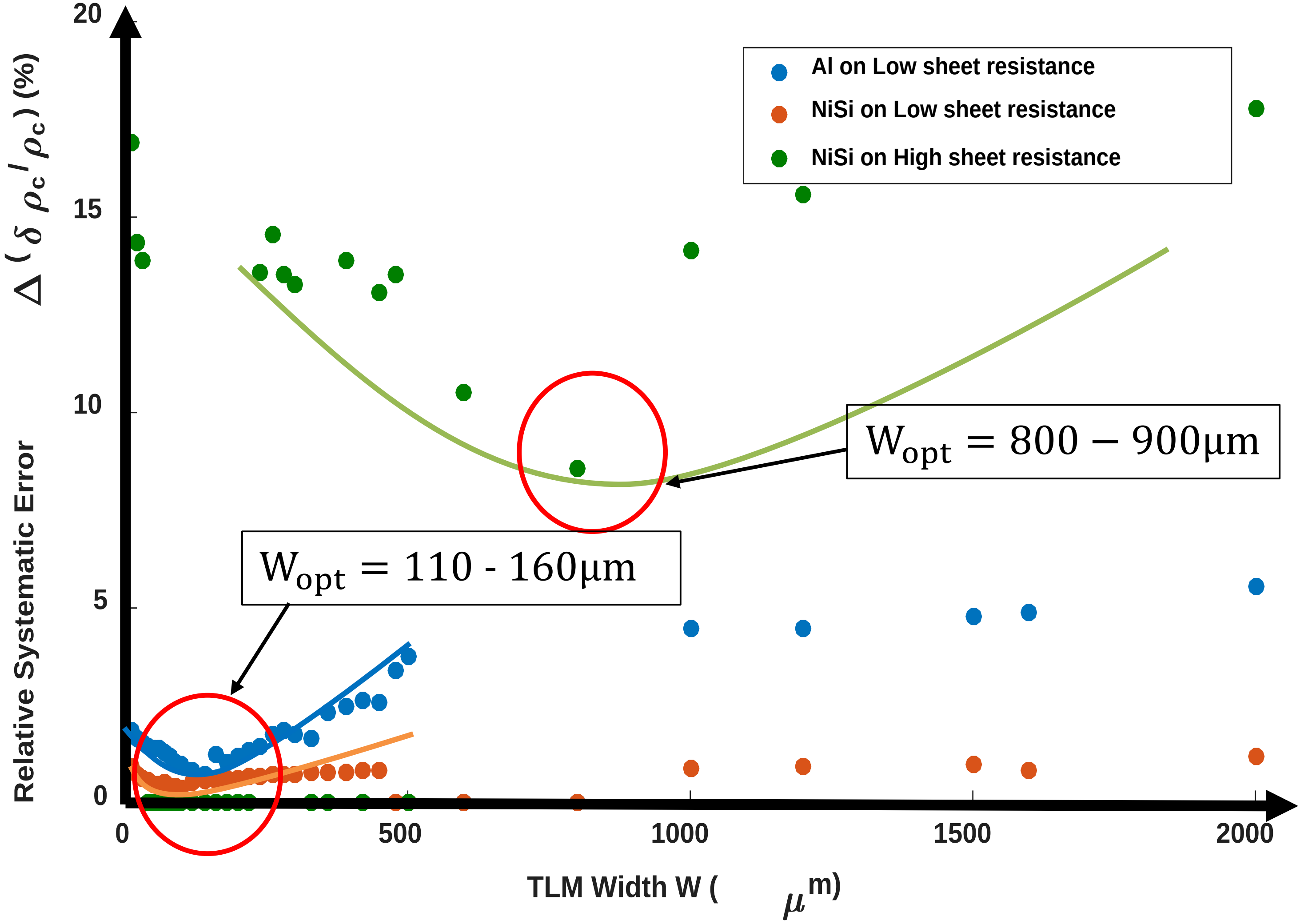
$R_{SH} \sim 1500\ \Omega/\square$
Metals – Al and NiSi

$R_{SH} \sim 50\ \Omega/\square$
Metals – Al and NiSi

Systematic Error Results

Aluminum on high Rs gave schottky contact behavior.

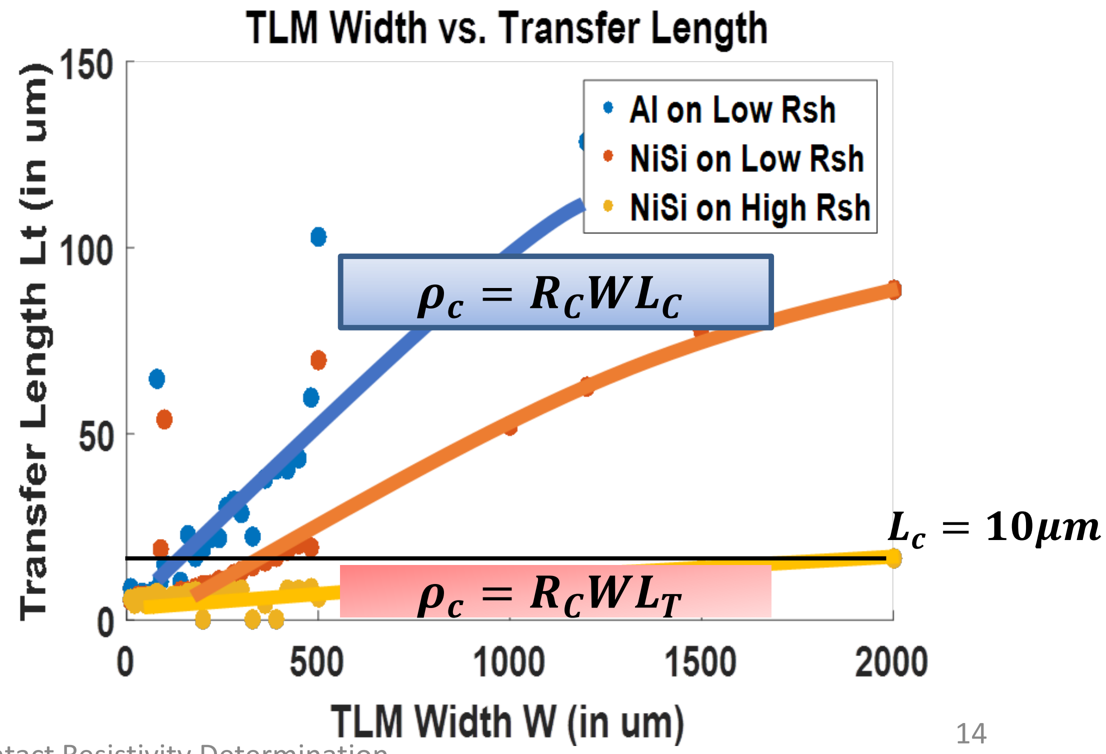
Parameter	W_{opt} (μm) Simulated	W_{opt} (μm) Fabricated
NiSi on High Rs	900	800
NiSi on Low Rs	150	115
Al on Low Rs	150	115



Experimental Results

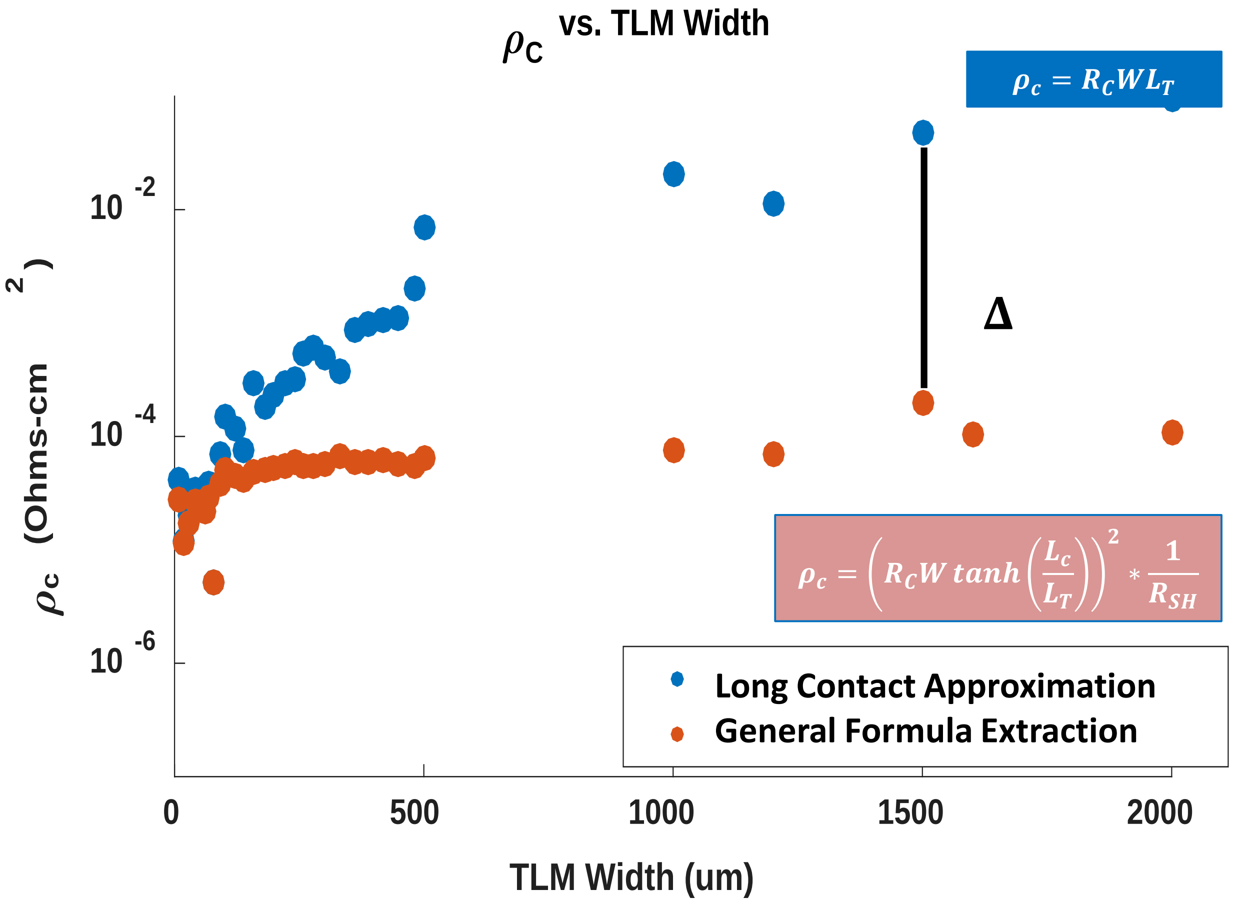
- TLM measurement of optimum width structures gave ρ_c values that were relatively similar to anticipated values.
- A proportionality was observed between the transfer length (L_T) and TLM width (W).
- Since ρ_c depends on L_T, optimum width value for a specific application may give inconsistent results.

#	Metal	ρ_c $(\Omega-\mathrm{cm}^2)$ Anticipated	R_{SH} $(\Omega/sq.)$ Fabrication	$W_{opt}(\mu m)$ Error Analysis	$L_T(\mu m)$ Extracted	ρ_c $(\Omega-\mathrm{cm}^2)$ Extracted
1	*NiSi*	$\sim10^{-5}$	50	115	9.3	$2\,\mathrm{x}10^{-5}$
2	*NiSi*	$\sim10^{-3}$	1500	800	9.65	$1\,\mathrm{x}10^{-3}$
3	*Al*	$\sim10^{-5}$	50	115	10.4	$4.5\,\mathrm{x}10^{-5}$



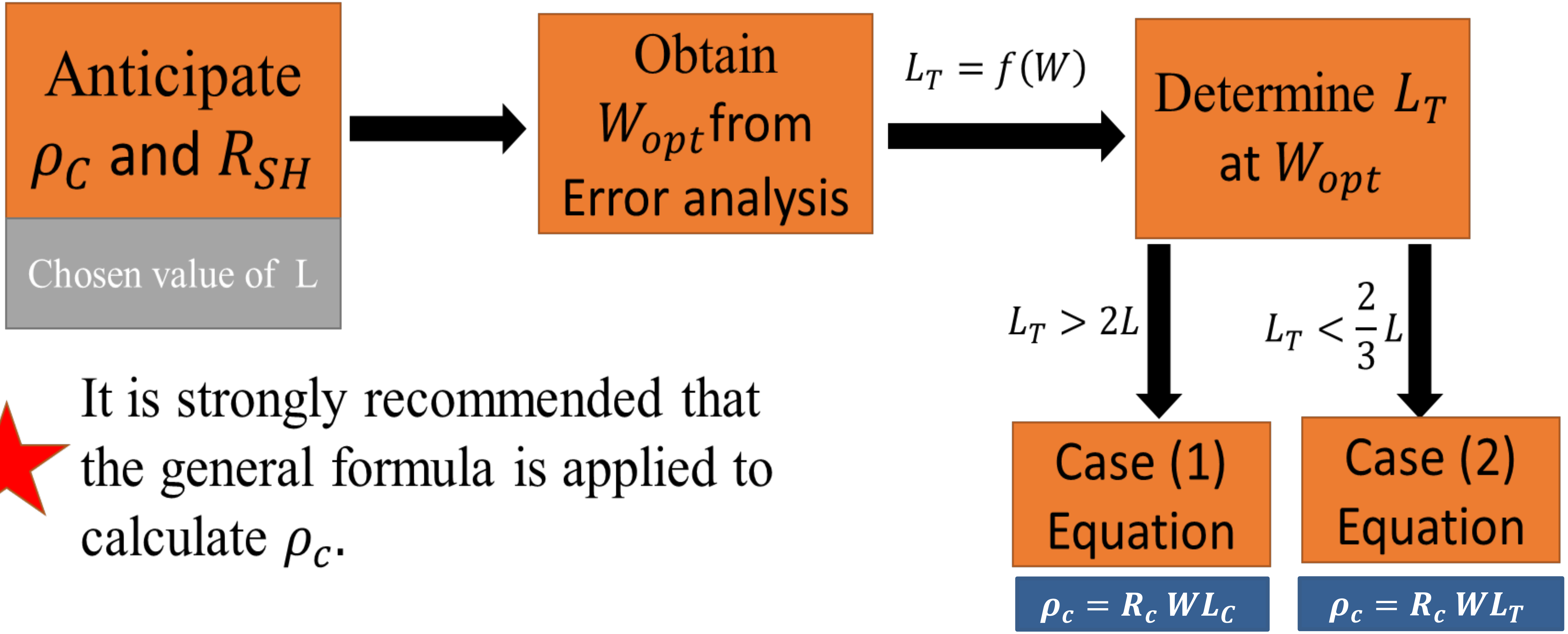
Experimental Results

- ρ_C extraction from the long contact approximation (inconsistent use in literature) gave overestimated results.
- Comparison between use of both extraction equations gave over a couple of orders of magnitude Δ
- This Δ can give erroneous results if obtained from non-optimized TLM width values.
- Therefore, an approach to accurately determine ρ_C and R_{SH} from the TLM method needs to be developed for a given application space.



Conclusion

- A process to accurately determine ρ_C from the TLM method is suggested –



★ It is strongly recommended that the general formula is applied to calculate ρ_c.

Future Work

- Further understanding is necessary on the interaction between L_T and W
- The effect of varying TLM length needs to be investigated
- Optimize general TLM formula and suggest optimum dimensions for varying R_{SH} and ρ_C
- Develop a standardized approach for accurate measurement of specific contact resistivity through TLM measurements for a given application and simultaneously compare with universal Cross Bridge Kevin Resistance (CBKR) curves.
- Investigate the use of different metals and/or metallization schemes.

References

[1] G. K. Reeves and H. B. Harrison, "Obtaining the specific contact resistance from transmission line model measurements," in *IEEE Electron Device Letters*, vol. 3, no. 5, pp. 111-113, May 1982.

[2] Haw-Jye Ueng, D. B. Janes and K. J. Webb, "Error analysis leading to design criteria for transmission line model characterization of ohmic contacts," in *IEEE Transactions on Electron Devices*, vol. 48, no. 4, pp. 758-766, Apr 2001.

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