Electrical contacts: A voltage scale for thermal runaway and issues in measurements of constriction resistance

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Outline

- Introduction
- Voltage scale for Electro-Thermal runaway
- Issues on experimental measurement of constriction resistance
- Conclusions and future works

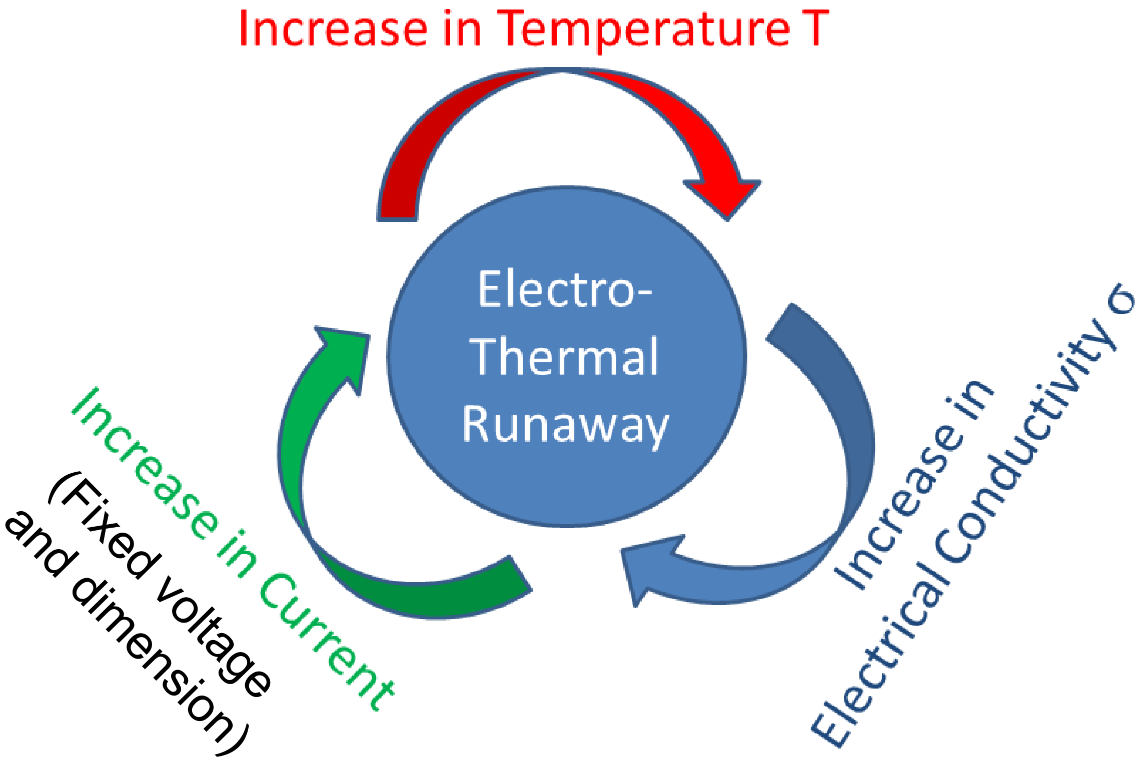
Introduction

- Contact problems account for 40 percent of all electrical/electronic failures

- Severe heating due to local current constrictions at thin film contacts [1-3] and at bulk contacts [2,4] is also a concern to high power microwave sources, pulsed power systems, field emitters, thin film devices and integrated circuits, and interconnects, etc.

1. P. Zhang, Y. Y. Lau, and R. S. Timsit, IEEE Trans. Electron Devices **59**, 1936 (2012).
2. P. Zhang, doctoral dissertation, University of Michigan, Ann Arbor (2012).
3. P. Zhang, D. Hung, and Y. Y. Lau, J. Phys. D: Appl. Phys. **46**, 065502 (2013); Corrigendum, ibid, 46, 209501 (2013).
4. P. Zhang and Y. Y. Lau, IEEE J. Electron Dev. Soc. **1**, 83 (2013).

Electro-Thermal Runaway: A Positive Feedback



- We investigate one aspect of electro-thermal instabilities, namely, the increase in electrical conductivity as the temperature increases, as typical of semiconductors.
- This may lead to thermal runaway, at a fixed voltage.

Heat Conduction Equation

$$C\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} + J \bullet E$$

C: Heat capacity
T: Temperature
κ: Thermal conductivity
J: Current density
E: Electrical field

Heat Conduction Equation

Assume electrical conductivity σ increases as temperature T increases, typical for semiconductors

$$\sigma(T) \approx \sigma_0 + \sigma_0' T$$

⇒

$$J \bullet E = \sigma(T) E^2 = (\sigma_0 + \sigma_0' T) E^2$$

Heat Conduction Equation

➡

$$C\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} + (\sigma_0 + \sigma_0{}'T)E^2$$

Assume $T \sim e^{jkx}$

➡ $$C\frac{\partial T}{\partial t} - \left[\sigma_0{}'E^2 - \kappa k^2\right]T = \sigma_0 E^2$$

Heat Conduction Equation

$$\frac{\partial T}{\partial t}-\underbrace{\left[\frac{\sigma_0{}'E^2-\kappa k^2}{C}\right]}_{S}T=\frac{\sigma_0}{C}E^2$$

If $S > 0$, $T \sim e^{St}$, i.e. thermal instability

Voltage Scale for Electro-Thermal Runaway

$$S = \left[\frac{\sigma_0' E^2 - \kappa k^2}{C} \right] > 0$$

⇒

$$E > \sqrt{\frac{\kappa k^2}{\sigma_0'}}$$

Multiply both sides by a length L

$$EL > (kL)\sqrt{\frac{\kappa}{\sigma_0'}}$$

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Voltage Scale for Electro-Thermal Runaway

$$EL > (kL)\sqrt{\frac{\kappa}{\sigma_0{}'}} = (kL)V_s$$

There is a voltage scale V_s, which characterizes thermal runaway

$$\boxed{V_s = \sqrt{\frac{\kappa}{\sigma_0{}'}}}$$

κ: Thermal conductivity [W/(mK)]

σ_0': Rate of change of the electrical conductivity with respect to temperature [1/(ΩmK)].

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Voltage Scale for Electro-Thermal Runaway

$$\boxed{V_s = \sqrt{\frac{\kappa}{\sigma_0{}'}}}$$

Note: V_s depends only on material properties and is independent of geometry or the operating voltage. It measures the intrinsic tolerance of the material to electro-thermal instability.

Voltage Scale for Electro-Thermal Runaway

	κ [W/(m-K)]	σ_0' [1/(Ω-m-K)]	V_s [Volt]
Si	**142**	**0.0012-0.7**	**14.2-348.9**
Ge	**58**	**0.0001-0.05**	**34-761.6**
C (graphite)	**127**	**1.67×10^{-4}-8.33×10^{-6}**	**872.9-3903.8**
SiC	**370**	**4×10^{-7} or negative**	**3×10^{4}**

SiC is the most resistant to thermal runaway for the same geometry and the same operating voltage, consistent with the well-known property of this material

Experimental measurement of constriction resistance

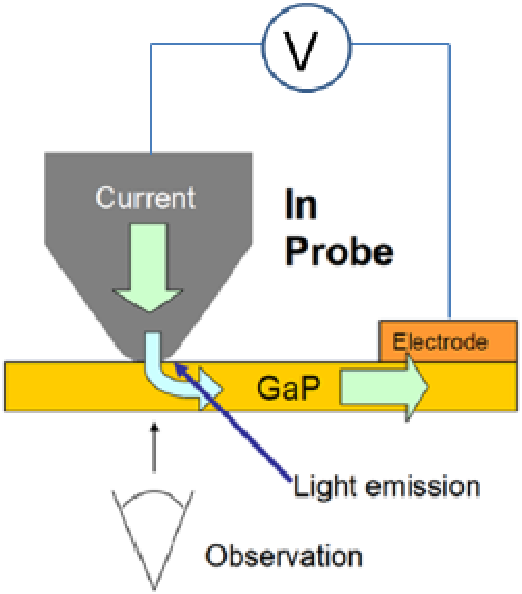
$$R_{Total} = V/I$$

$$R_c = R_{Total} - R_{bulk}$$

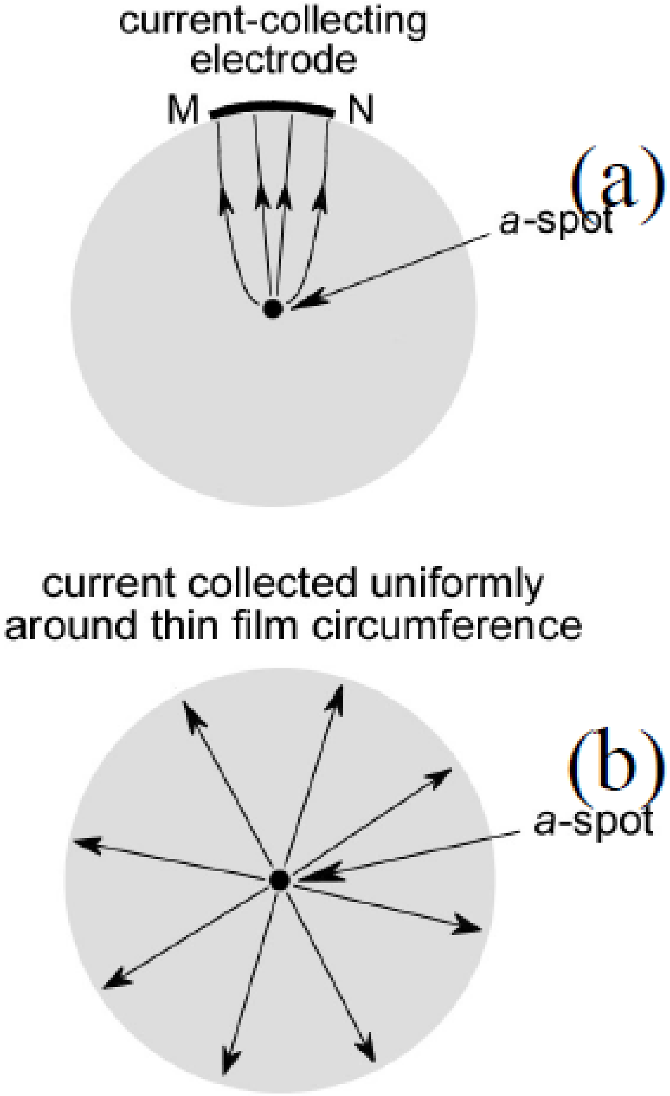
How to accurately estimate R_{bulk} is very important!

There is **arbitrariness** in the decomposition of R_{Total} into R_s and R_{bulk}

Experimental measurement of constriction resistance



S. Sawada, et al, Proc. 58th IEEE Holm Conf. on Electrical Contacts, Portland, OR, 242 (2012).

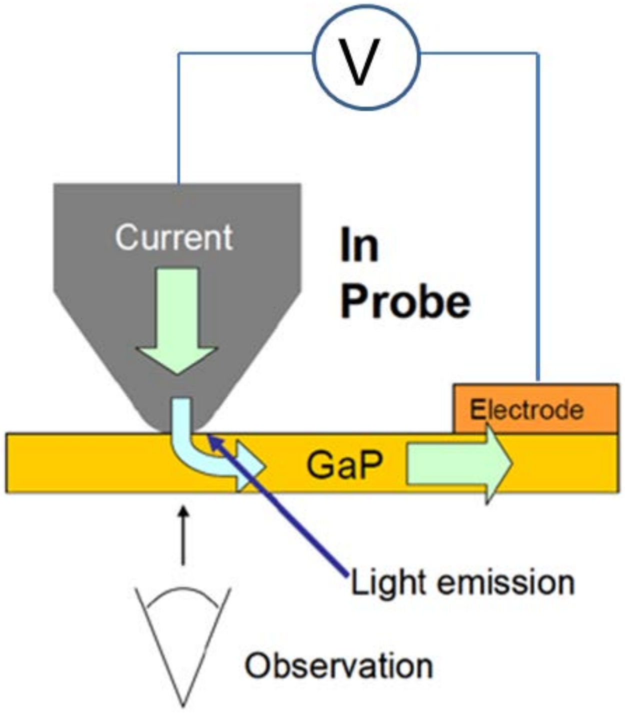


- Case (a) greatly influences R_{bulk} and also complicates its evaluation
- Model (b) underestimates R_{bulk} of case (a)

Additional sources of uncertainty in two-terminal measurement

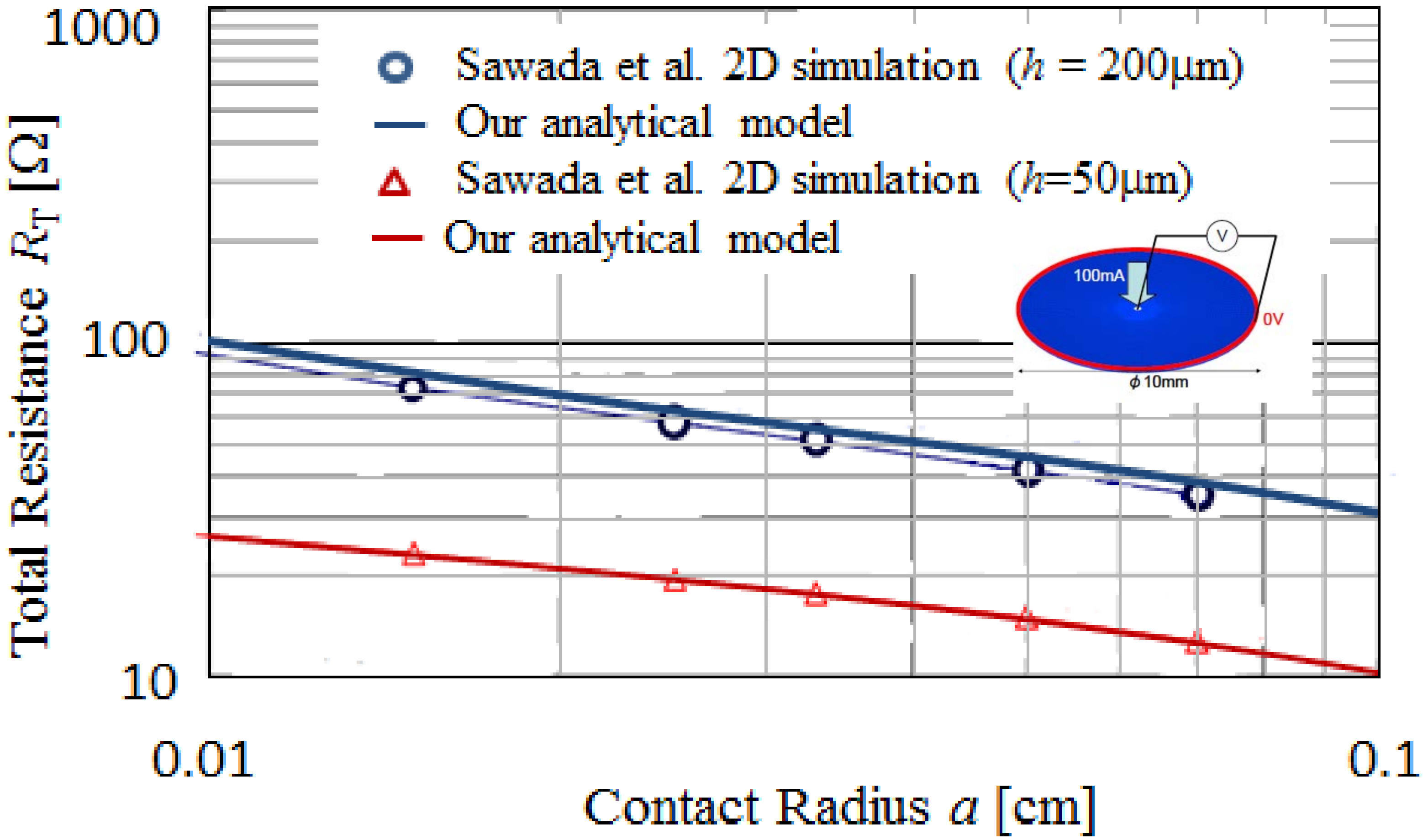
- Unavoidable contact resistance at the measuring electrodes

- Spreading resistance at the current collecting electrode



We have case (a) here

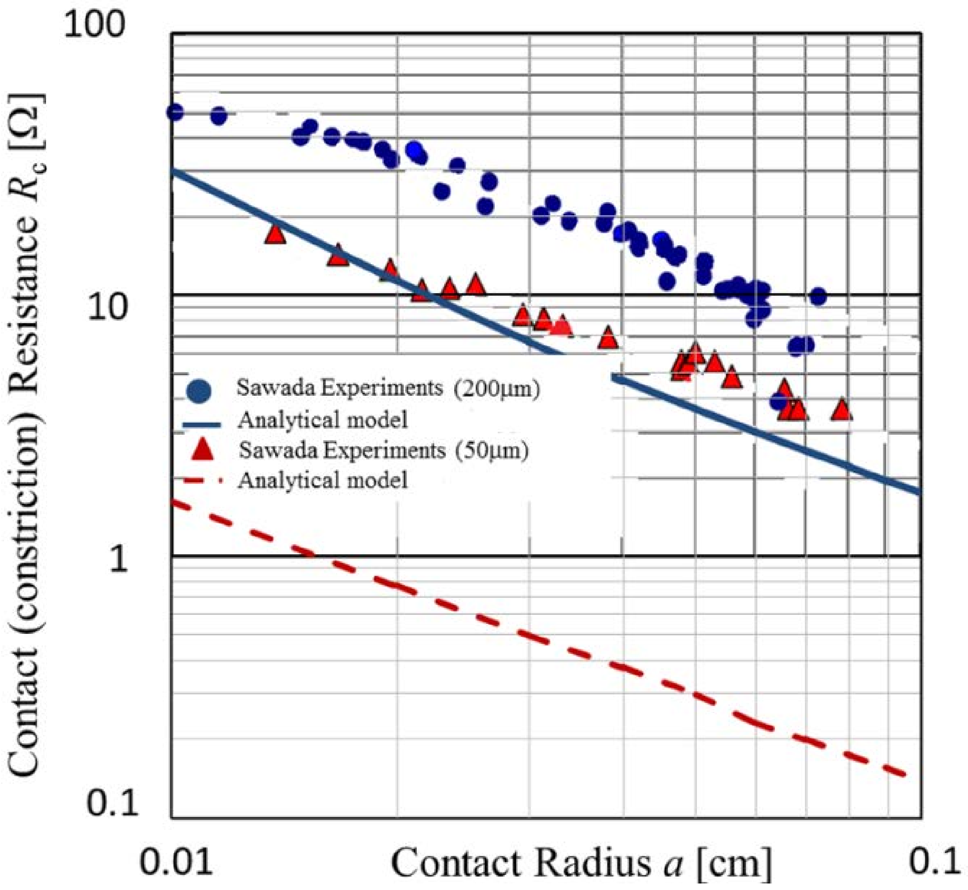
Theory vs. 2D cylindrical simulation

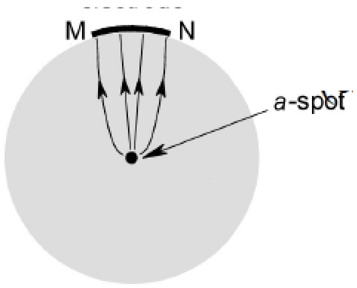


Good agreement due to same geometry used in simulation and theory

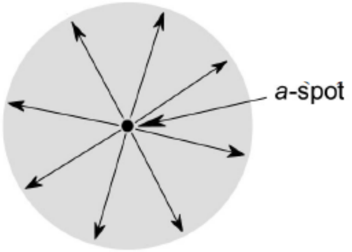
S. Sawada, et al, Proc. 58th IEEE Holm Conf. on Electrical Contacts, Portland, OR, 242 (2012).

Theory vs. Experimental measurement of constriction resistance[1]





Experiment



Theory

Potential errors[2] in estimating R_{bulk}

[1] S. Sawada et al, Proc. 58th IEEE Holm Conf. on Electrical Contacts, Portland, OR, 242 (2012).

[2] P. Zhang, Y. Y. Lau, R. S. Timsit, 59th IEEE Holm Conf. on Electrical Contacts, Newport, RI (2013).

Conclusions

- Made vast generalization in theory of electrical contact, for both bulk and thin-film contacts (applicable to high power microwave sources, field emitters, thin-film devices, MEMS, interconnects, etc).

- Voltage scaling developed for electro-thermal runaway.

- Issues in experimental measurement of constriction resistance are discussed.