Cu-Bi as a Model System For Liquid Phase Sintered Thermal Interface Management Materials

P. Rottmann, J. Liu, P. Kumar, I. Dutta

Background and Introduction

Liquid phase sintering (LPS) is a manufacturing process used to produce composite materials. A high melting phase (HMP) and low melting phase (LMP) are mixed and compressed. The powders are then brought above the melting temperature of the LMP whereupon densification takes place as the LMP spreads around the solid HMP particles; the reduction of the surface energy of the system provides the driving force for the elimination of pores.

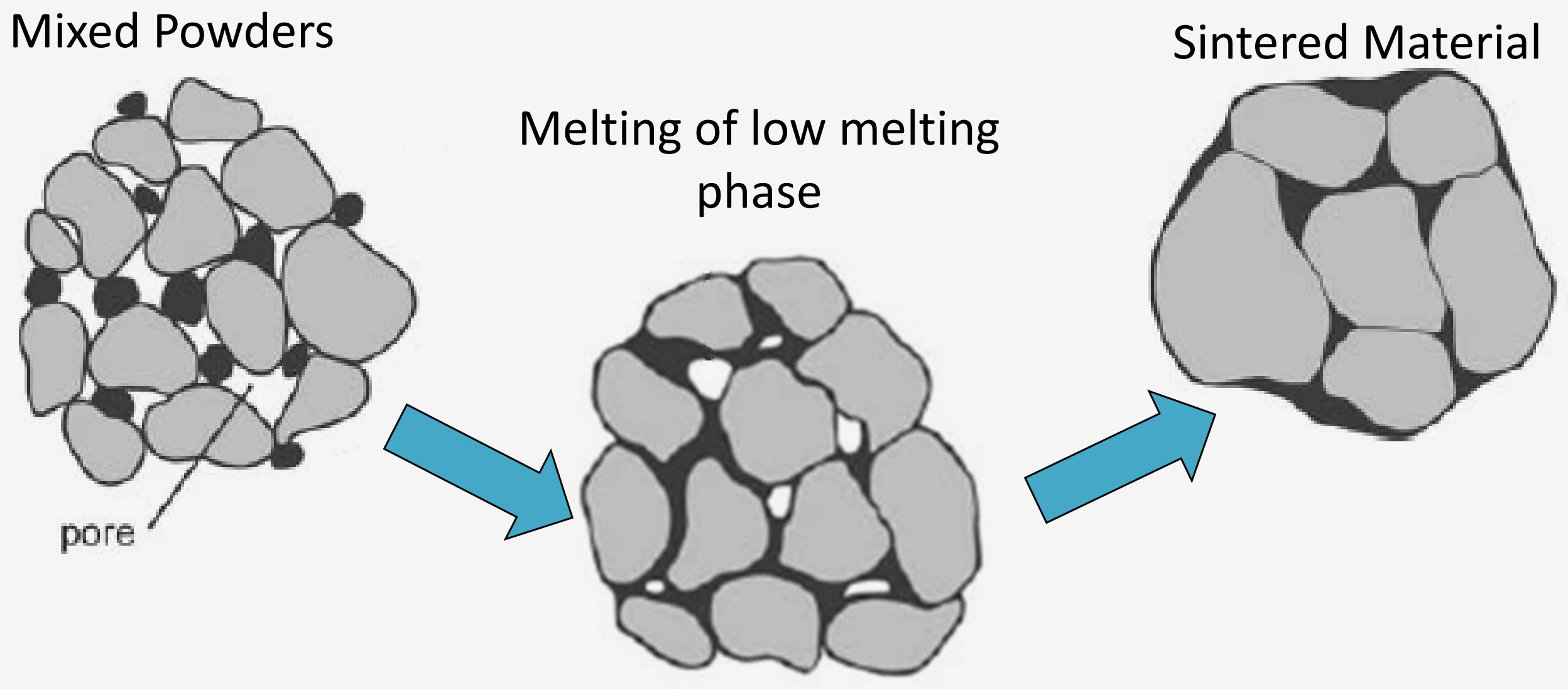
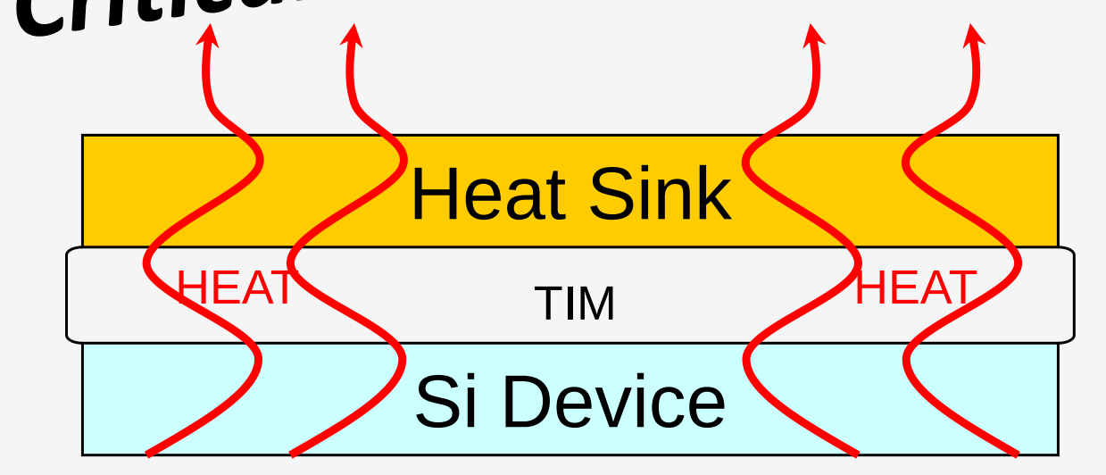


Figure 1. Liquid phase sintering process [1]

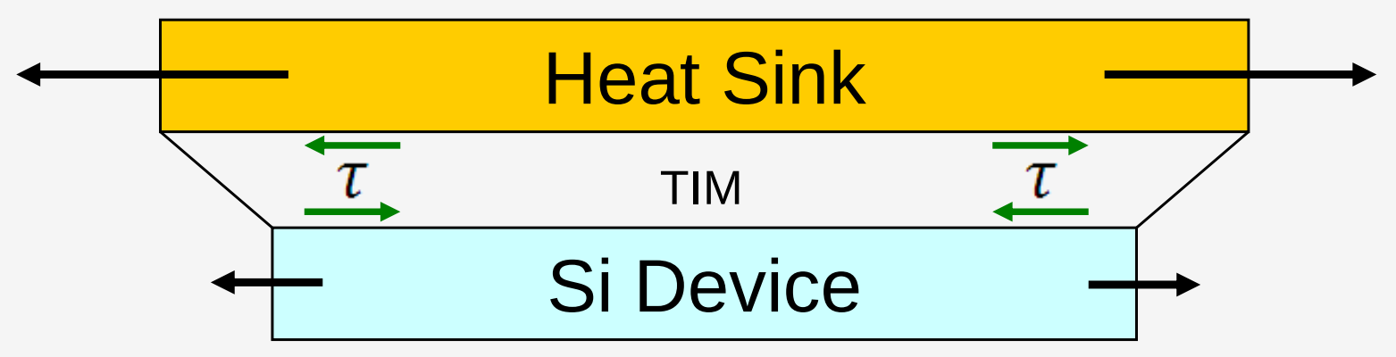
Thermal Interface Materials (TIM) are used in microelectronics to join the silicon device that houses all of the circuit elements to a material that can quickly radiate heat produced during operation.

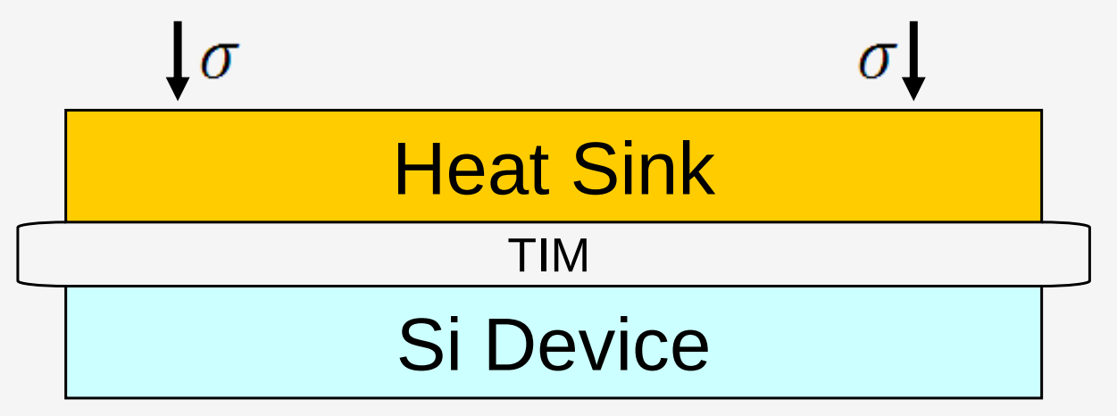
Critical TIM Properties



1) High thermal conductivity to conduct heat from silicon device to heat sink

2) High compliance in shear to accommodate for differences in thermal expansion of silicon and heat sink





3) Good tensile creep properties to support weight of heat sink

The purpose of this investigation is to demonstrate that composites constructed via LPS exhibit beneficial and controllable properties that can be tailored for use in TIM applications.

A 50-50 volume percent Cu-Bi solder was chosen as a model system with which the benefits of introducing LPS composites into TIM applications could be determined. Cu-50Bi solder was chosen because:

- ➢ Large difference in melting temperature (T_m(Cu)=1084.6 C; T_m(Bi)=271.3 C),
- ➢ Mutual insolubility
- ➢ Very good wetting (dihedral angle of 0) between copper and liquid bismuth. [2]

Experimental Procedure and Results

Microstructure. 5mm diameter Cu-50Bi pellets were manufactured using different processing parameters in order to determine that a well-sintered pellet could be produced. Pellets up to 97% dense with nearly perfect wetting of copper-bismuth interfaces were produced (Figure 2).

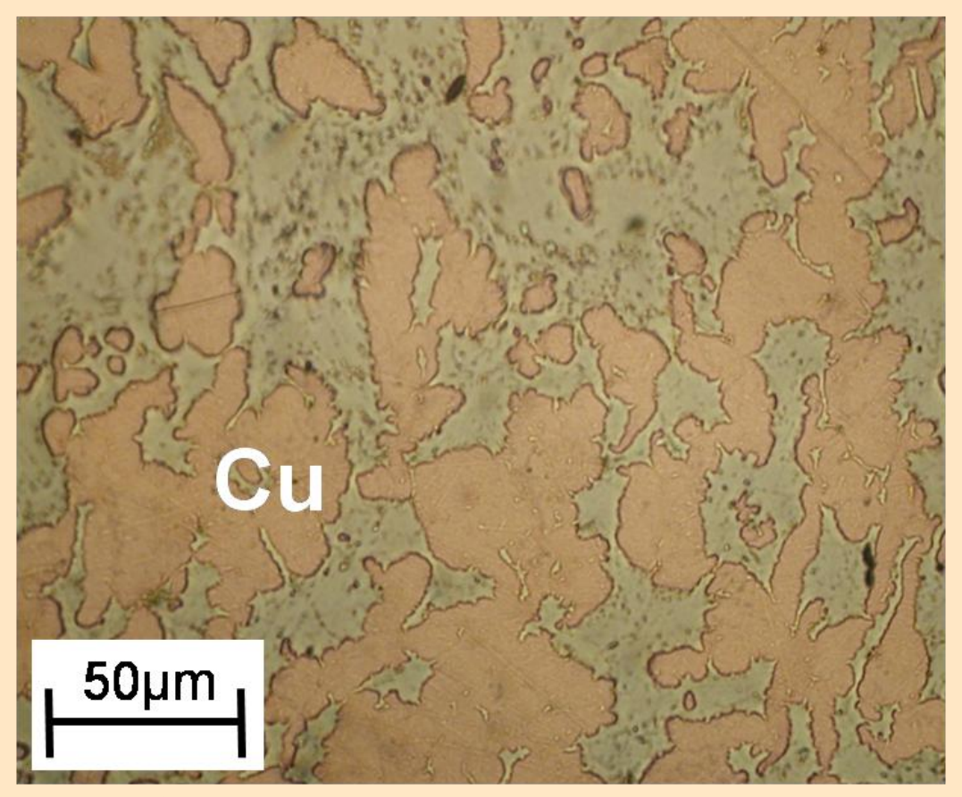


Figure 2. Representative microstructure of Cu-50Bi LPS solder

Thermal Conductivity. The thermal conductivity of solder pellets was calculated using electrical resistivity measurements obtained from a Kelvin probe. The Wiedemann-Franz Law relates electrical resistivity to thermal conductivity for materials where electrons are principle carriers:

$$\kappa\rho = LT \qquad \kappa = Thermal\ conductivity \quad T = Temperature$$

$$\rho = Electrical\ resistivity \quad L = 2.44 * 10^{-8}\frac{W\Omega}{K^2}$$

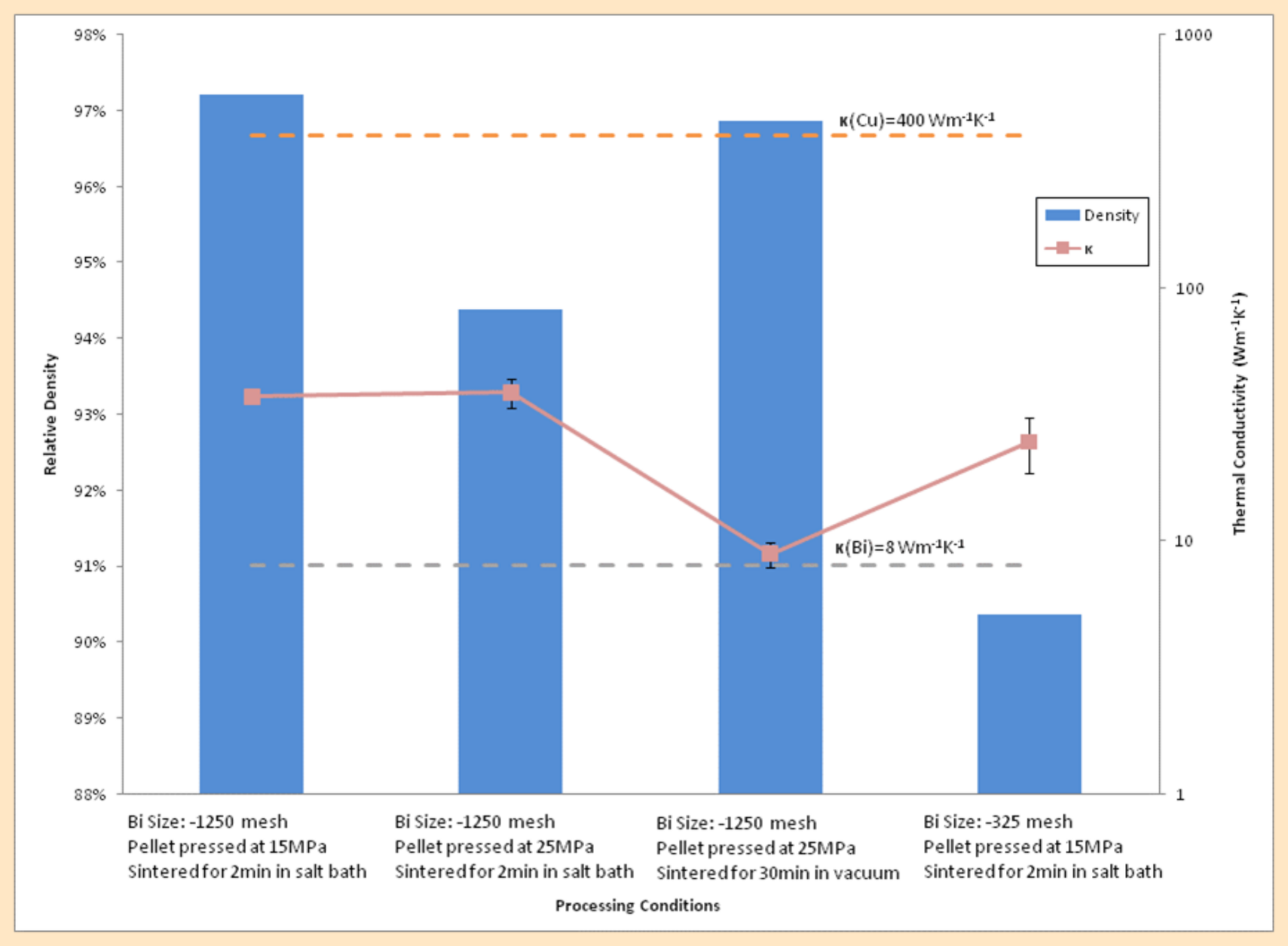


Figure 3. Achievable sintered density using different processing conditions and respective thermal conductivity

- Ideal processing conditions for maximum sintered density and thermal conductivity:
  - -1250 mesh (10μm) bismuth; -325 mesh (44μm) copper
  - Sintered in 300 C salt bath for 2 minutes
- Cu-50Bi LPS solder has a **thermal conductivity of 37 Wm^{-1}K^{-1} which is significantly higher than bismuth (8 Wm^{-1}K^{-1})**

Mechanical Properties. Stress-strain plots of Cu-Bi LPS solder were produced using impression testing ($\varphi_{Ind} = 250\mu m$).

- Tests were done at 265 C and 278 C to determine increase in compliance as Bi melts
  - LMP solders will be designed so that T_m(LMP) will be below operating temperatures
- Punch stress-strain rate plots were constructed to determine strain rate sensitivity at each temperature (Figure 5).

$$\sigma = A\dot{\varepsilon}^m \qquad \sigma = Stress \quad \dot{\varepsilon} = Strain\ rate$$

$$m = Strain\ rate\ sensitivity$$

- **Strain rate sensitivity measured to be close to 0.1** both below and above bismuth melting point
- **Flow stress decreases by a factor of ~3 above melting point of bismuth**

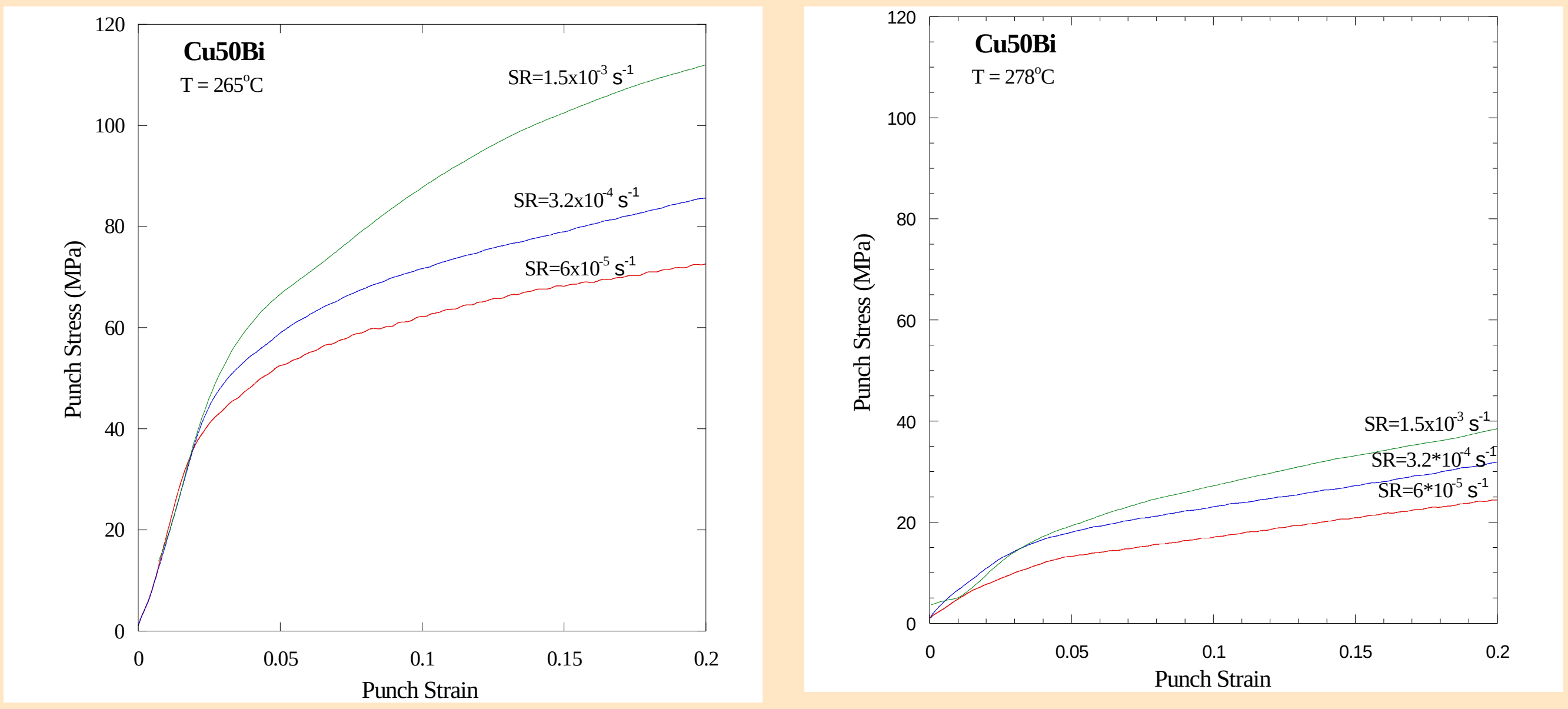


Figure 4. Punch stress-punch strain curves from impression tests run below (left) and above (right) melting point of bismuth

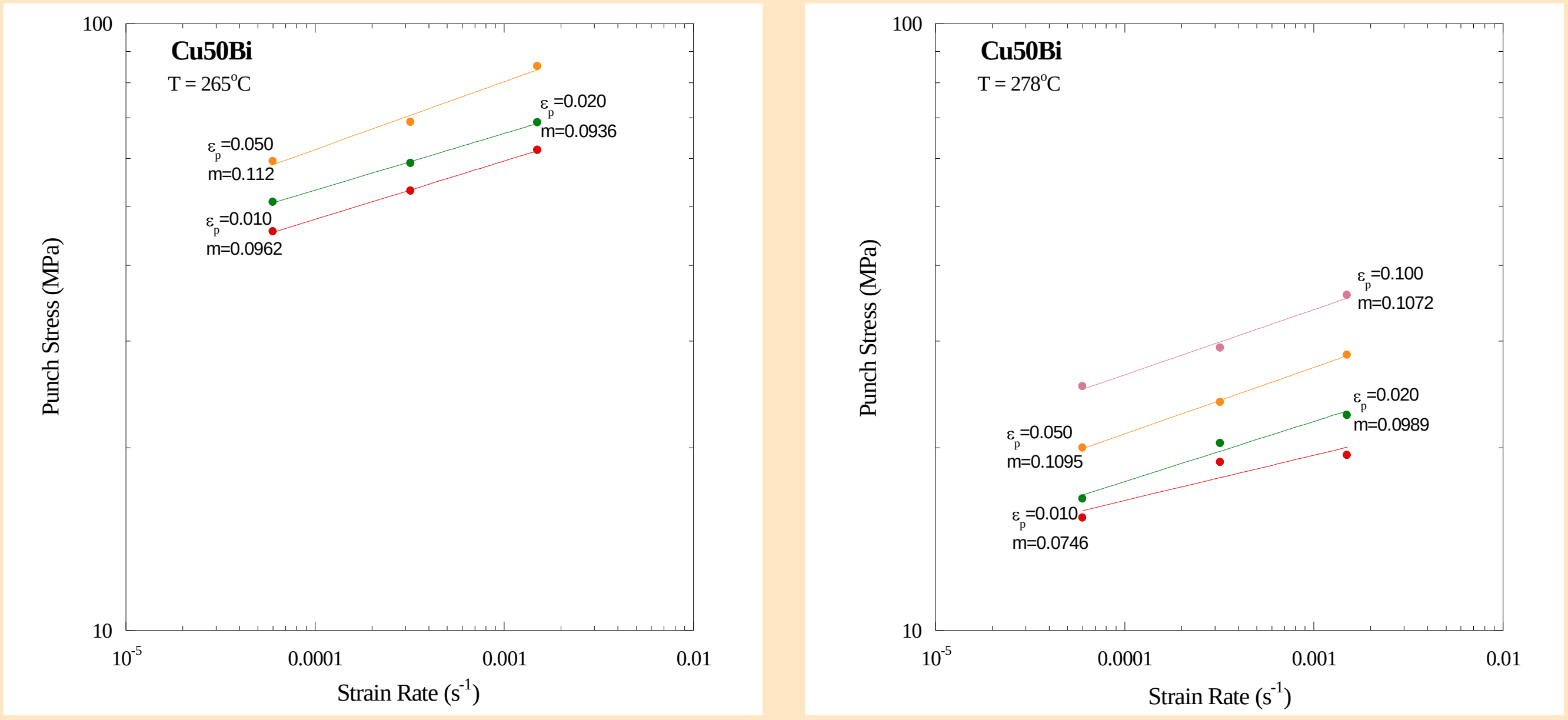


Figure 5. Punch stress-strain rate plots from impression tests run below (left) and above (right) melting point of bismuth. Each line at constant plastic strain

Modeling.

$$R_C^{th} = \frac{D}{2V_{Cu}}\left(\frac{1}{\kappa_{meas}} - \frac{V_{Bi}}{\kappa_{Bi}} - \frac{V_{Cu}}{\kappa_{Cu}}\right)$$

$$a_k = R_C^{th}\kappa_{Bi} = Kapitza\ radius$$

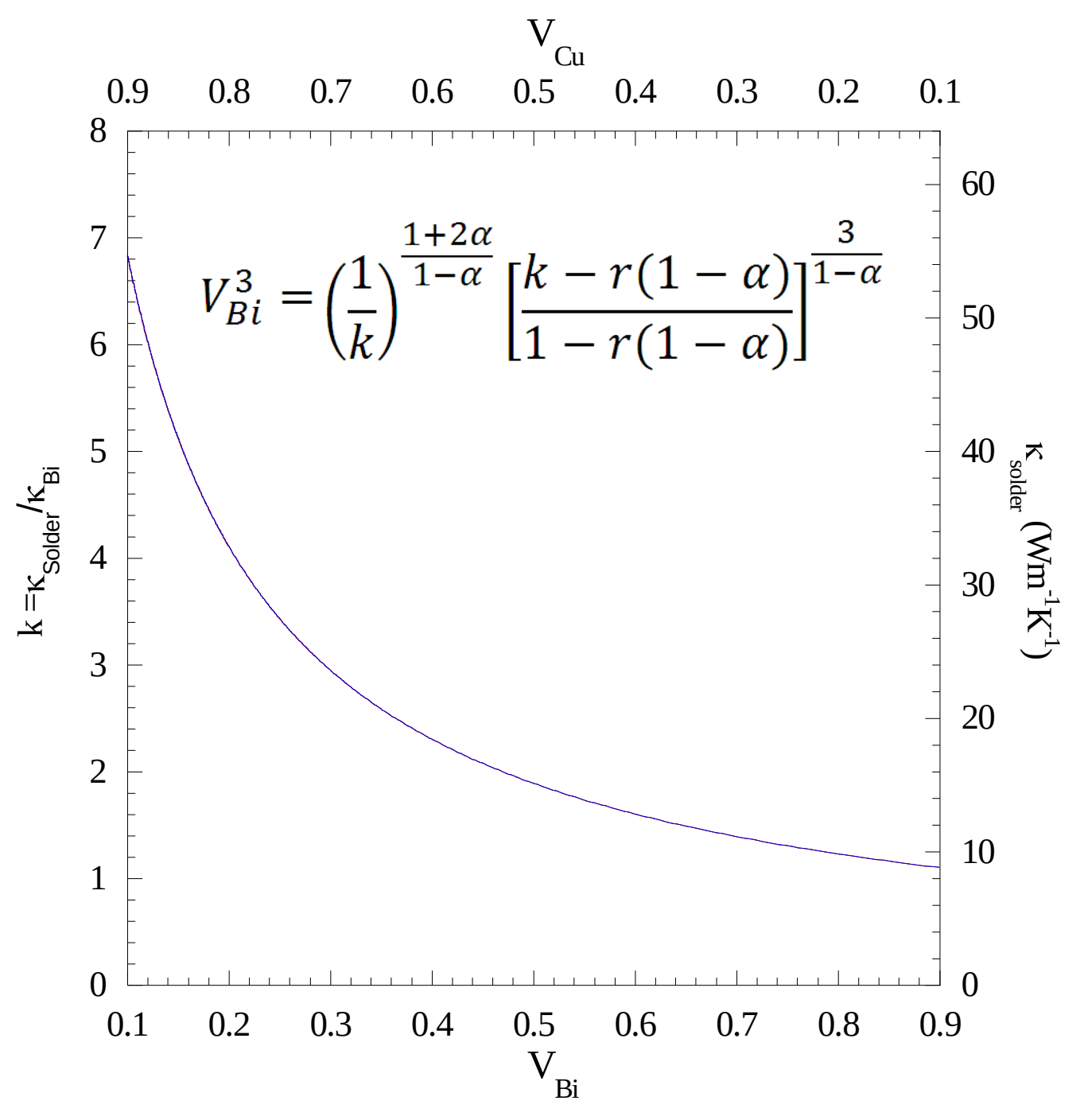
$$\alpha = \frac{2a_k}{D} \quad k = \frac{\kappa_{Solder}}{\kappa_{Bi}} \quad r = \frac{\kappa_{Cu}}{\kappa_{Bi}}$$

$$R_C^{th} = Thermal\ contact\ resistance$$

$$D = Cu\ particle\ size$$

$$V_i = Volume\ fraction$$

$$\kappa_i = Thermal\ conductivity$$



$$V_{Bi}^3 = \left(\frac{1}{k}\right)^{\frac{1+2\alpha}{1-\alpha}}\left[\frac{k - r(1-\alpha)}{1 - r(1-\alpha)}\right]^{\frac{3}{1-\alpha}}$$

Figure 6. Thermal conductivity of Cu-Bi solder as a function of Bi fraction

- Kapitza radius of 0—**Cu particle size will not affect thermal conductivity** [3]
- Thermal conductivity decreases rapidly as Bi volume fraction approaches 0.3; after which additional Bi has minimal impact

Conclusions.

- High thermal conductivities intermediate of those of constituent materials attainable through LPS solders
- Melting of LMP provides a sharp decrease in stress required for plastic flow
- Shear testing will need to be done on LPS solders to better model strain rate sensitivity
- Good contact between HMP and LMP negates effect of HMP size
- All obtained results suggest that LPS solders exhibit thermal and mechanical behavior desirable for TIM applications

Sources.

[1] German R.M, Suri P, Seong JP (2009) J Mater Sci **44**:1-39.
[2] Vaandrager BL, Pharr GM (1989) Acta Metall Vol. 37 No. 4 1057-1066
[3] Dutta I et al (2009) Journal of Electronic Materials in press

Acknowledgments.

This work was supported by the National Science Foundation's Research Experience for Undergraduates program under grant number DMR-0755055