Heat transport across the metal-diamond interface

I. Introduction

- Miniaturization of electronic devices and increasing density of electronic components on a single chip require proper heat-sink materials.
- Metal-diamond composites are good heat sink materials because they have enhanced thermal conductivity upto 670 W/mK.
- Nowadays synthetic diamonds are produced in large scale by applying high pressure to carbon and available at low cost.

- Although several studies have addressed the formation of metal-diamond interfaces, but understanding of the heat conduction mechanism across the metal-diamond interface **is not yet addressed**.

II. Experiments

Preparation of Al-diamond interface

Gas pressure infiltration

Stead state technique for thermal conductivity measurement

Scanning electron microscope of Al-diamond composite

IV. Conclusion

- Gas pressure infiltration method is successfully employed to prepare Al-diamond composites.
- SEM pictures show the formation of strong interfacial bonding in the composite.
- Steady state technique is used to measure the thermal conductivity of composites.
- Electron-phonon coupling in the Al and phonon-phonon coupling at the interface are responsible for heat transport across Al-diamond composites.
- Scattering mediated acoustic mismatch model explains the measured thermal conductivity more accurately.

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References: P.W. Ruch, O. Beffort, S. Kleiner, L. Weber, P. J. Uggowitzer, 2006, Comp Sci Tech, 66, 15, 2677-2685.

III. Interface Thermal Resistance (ITR)

(a) Experimental data

- By using Steady State Technique, thermal conductivity of Al-diamond composite (λ_c) is measured to be 670 W/mK.
- Experimental interface thermal resistance (ITR) ($5.43 \times 10^{-9} \text{ m}^2\text{K/W}$) is determined using the Hasselman and Johnson model.

$$\lambda_c = \lambda_m \left[\frac{2 \left(\frac{\lambda_d}{\lambda_m} - 1 - \frac{\lambda_d}{ah} \right) V_d + \left(\frac{\lambda_d}{\lambda_m} + \frac{2\lambda_d}{ah} + 2 \right)}{\left(1 - \frac{\lambda_d}{\lambda_m} + \frac{\lambda_d}{ah} \right) V_d + \left(\frac{\lambda_d}{\lambda_m} + \frac{2\lambda_d}{ah} + 2 \right)} \right]$$

λ_d and λ_m are the thermal conductivity of diamond and Al respectively.
 V_d and a are the volume content and radius of the dispersed diamond particles respectively.
 $1/h$ is the experimental ITR value.

(b) Theoretical model to explain the experimentally measured ITR data

- ITR is not equal to zero even when two materials are similar. This is called Kapitza paradox.

- At the Al-diamond interface, the thermal conduction is expected to take place by coupling between electrons and phonons within the Al, and then subsequent coupling between phonons of the Al and phonons of the diamond (due to weak electron-phonon interaction in Al).

$$R_{NE} = 2 \left(\frac{\lambda_e}{\lambda_{ph}} \right) \left(\frac{\delta}{\lambda_{ph} + (\lambda_e + \lambda_{ph})} \right) \left(\frac{e^{L/\delta} - 1}{e^{L/\delta} + 1} \right)$$

L is the thickness of Al and G is the electron-phonon coupling constant.

$$\text{Electron-phonon coupling distance } \delta_{Al} = \left[\frac{\lambda_e \lambda_{ph}}{G(\lambda_e + \lambda_{ph})} \right]^{1/2}$$

$$\delta_{Al} = 4.42 \text{ nm}$$

$$\text{Hence, } R_{NE} = 1.8 \times 10^{-9} \text{ m}^2\text{K/W}$$

- Acoustic mismatch model (AMM), diffuse mismatch model (DMM) and scattering mediated acoustic mismatch model (SMAMM) explain the ph-ph couplings.

- R_b is calculated from the phonon-phonon (ph-ph) coupling at the interface.

- SMAMM takes all the phonon scattering (grain boundary scattering, scattering due to strain effects, ph-ph Umklapp scattering) mechanisms into account at the interface.

Parameter	Diamond	Al
Phonon velocity	18'190 m/s	6'296.3m/s
Debye temperature	2200 K	428K
Thermal conductivity	~2000W/mK	343 W/mK

Large mismatch

Phonon scattering rate is effected by the grain boundary scattering, inelastic scattering and lattice imperfections and can be expressed as a kind of Methiessen's rule as:

$$\tau_{ph}^{-1} = \tau_b^{-1} + KTx + Ux \exp\left(-\frac{\Theta_D}{bT}\right)$$

Net heat flux q is given as

$$q = \frac{3}{4\pi^2} \frac{1}{v_1^2} \int_0^{\pi/2} \int_0^{\pi/2} \int_0^{\pi/2} \frac{1}{\exp\left(\frac{\hbar\omega}{k_b T_2}\right) - 1} - \frac{1}{\exp\left(\frac{\hbar\omega}{k_b T_1}\right) - 1} \alpha(\theta, \omega) \sin(\theta) \cos(\theta) d\omega d\theta$$