Assessment of defects and quality of thin films and interfaces with laser-based thermoreflectance thermal conductivity measurements

Patrick E. Hopkins[a,b,c,d,*], John T. Gaskins[d], Md. Rafiqul Islam[a], Md. Shafkat Bin Hoque[e], Eric R. Hoglund[f], Saman Zare[a], Pravin Karna[g], Ashutosh Giri[g], Seppe Van Dyck[h], Christophe Detavernier[h], Rinus T.P. Lee[i], Kandabara Tapily[i], Valeria Founta[j], Christoph Adelmann[j], Colin D. Landon[e], Christopher Jezewski[e], Sean W. King[e], Asif Khan[k], W. Alan Doolittle[l]

[a] *Dept. of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA 22904 USA*
[b] *Dept. of Materials Science and Engineering, University of Virginia, Charlottesville, VA 22904 USA*
[c] *Dept. of Physics, University of Virginia, Charlottesville, VA 22904 USA*
[d] *Laser Thermal, Charlottesville, VA 22903 USA*
[e] *Intel Corporation, Hillsboro, OR 97124 USA*
[f] *Oak Ridge National Laboratory, Oak Ridge, TN 37830 USA*
[g] *Dept. of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI 02881 USA*
[h] *Department of Solid State Sciences, CoCooN, Ghent University, Ghent B-9000 Belgium*
[i] *Tokyo Electron, Albany, NY 12205 USA*
[j] *IMEC, Leuven, B-3001 Belgium*
[k] *Dept. of Electrical Engineering, University of South Carolina, Columbia, SC 29208 USA*
[l] *School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA*

Mitigating temperature rises in 3D integrated circuits (IC) has resulted in thermal challenges across a wide range of manufacturing length scales, from the middle- to back end-of-line in the metals and dielectrics used for interconnects, hybrid bonds, and heat spreaders. This problem is compounded by the fact that the reduced dimension of materials compounded with defects and non-idealities that arise from heterogeneous integration and interfaces all lead to increased thermal resistances, and thus increased temperature rises. Thus, minimizing 3D IC temperature rises is directly correlated to ensuring that materials and interfaces that are fabricated across all length scales in a 3D IC have increased thermal conductivities and decreased interfacial thermal resistances (ITR), which is directly correlated to the density of defects and voids in the thin films and interfaces.

The first problem to mitigate thermal resistances of 3D ICs is to minimize reductions in thermal conductivity of low dimensional metals. Both the thermochemical and thermomechanical stability of Cu at these length scales, along with the strong reduction in both electrical and thermal conductivity due to length scales reducing to those less than its electronic mean free path has led to underperformance, which in part can be ascribed to deleterious heating effects.[1] While Ru and W interconnects are currently being evaluated, a range of additional metals and metallic systems (alloys, eutectics, 2D materials, and multilayers) are also of note due to their potential mechanical and thermal properties that are superior to Cu at the < 100 nm length scale. In this presentation, we will discuss our recent efforts in measurements of thermal conductivity and electron-phonon scattering rates of thin metal films for interest as next-generation metal interconnects,[2] including Ru, W, Ir, Pt, Mo, Co and Ta, along with 2D delafossite films and metal multilayers. We will discuss the use of various thermoreflectance techniques – including time-domain thermoreflectance (TDTR), frequency-domain thermoreflectance (FDTR), steady state thermoreflectance (SSTR),[3,4,5] and *Laser Thermal's* FASTR tool – to measure the thermal properties of thin films, including the in-plane a cross plane thermal conductivity of thin films of metals, dielectrics, multilayer metals, and 2D systems. We will show that the thermal conductivity measurements are directly related to defects and microstructure of these thin films, offering a unique, high-throughput assessment of film quality to aid in selection of metal interconnects.

The second problem to mitigate thermal resistances of 3D ICs is fabricating electrically insulating films (e.g., amorphous dielectrics, and AlN), from nanometer to micrometer scales, in contact with silicon while maintaining a combination of high thermal conductivity (for heat spreading) or low ITR (for hybrid bonding). This problem applies to a range of length scales and materials, ranging from the ITRs between amorphous dielectrics and/or metals used in hybrid bonds, to achieving high thermal conductivity electrical insulators in contact with Si for heat spreaders (e.g., AlN). With our thermoreflectance-based approaches, we will demonstrate the ability assess film and interface quality, including high thermal conductivity AlN films,[6,7] and dielectric and metal films buried hybrid bonded interfaces,[8] using measurements of thermal conductivity and ITR of nanoscale films both at the surface and interfaces that are buried sub-surface.

References: 1. *Nat. Comm.* **15**, 9167 (2024). 2. *Adv. Fun. Mat.* e11592. 3. *Nat. Rev. Method Primer* **5**, 55 (2025). 4. *Rev. Sci. Instrum.* **90**, 024905 (2019). 5. *J. Appl. Phys.* **126**, 150901 (2019). 6. *Appl. Phys. Lett.* **125**, 262201 (2024). 7. *ACS Nano* **15**, 9588 (2021). 8. *Adv. Func. Mat.* **30**, 1903857 (2020).[*]phopkins@virginia.edu