

QED Cooling of Electronics

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QED Radiations

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Abstract— Automobile engines cooled by radiators with circulating water are based on pool-boiling that began with the Industrial Revolution. Recently, researchers have claimed heat transfer based on pool-boiling experiments using water against porous 50 – 150 nm zinc oxide coatings may be made 10X more efficient than bare aluminum and copper surfaces. Indeed, nanostructured heat transfer surfaces are thought to supersede the traditional cooling fin. The increased area provided by the porosity of the nanoscale coating is given to explain pool-boiling heat transfer enhancement. However, the notion that porosity increases the heat transfer area in pool-boiling is one of classical physics that assumes temperature changes occur in the coating irrespective of its thickness. But QM and not classical physics is applicable to nanoscale coatings, porous zinc oxide or otherwise. QM stands for quantum mechanics. QM differs from classical physics by requiring the heat capacity of the atom to vanish in nanoscale coatings thereby precluding the conservation heat flow into the coating by an increase in temperature. Instead, conservation proceeds by the creation of QED induced non-thermal EM radiation. QED stands for quantum electrodynamics and EM for electromagnetic. Enhancement of heat transfer over bare surfaces therefore occurs as QED induced radiation is emitted from the coating and absorbed in the water surroundings. Even water coolant, let alone pool-boiling are not required as the emission of QED radiation from zinc oxide coatings may be air cooled from the ambient surroundings, the latter notion of great interest in cooling electronics. Indeed, air cooling by coating conventional electronics circuit elements with nanoscale zinc oxide or other suitable materials is especially attractive and perhaps the only possible way to cool submicron circuit elements in nanoelectronics. The emission of QED radiation from nanoscale coatings is not new, having been mistaken in thin films as reductions in thermal conductivity that continue to this day, examples of which are presented from the literature.

Keywords— *electronics cooling; quantum mechanics; quantum electrodynamics; conductivity; Joule heat.*

I. INTRODUCTION

Heat exchange began with the Industrial Revolution. Pool-boiling rapidly emerged as the way to cool engines using water to transfer heat to the ambient air surroundings. Modern-day automobile engines use pool-boiling with water to dissipate heat to the ambient air through finned radiators. Pool-boiling heat transfer efficiency is increased by providing the radiator with cooling fins to increase the area by which the heat is dissipated. Unlike the automobile, cooling fins in many technology applications such as electronics, pool-boiling is difficult, if not impossible to implement.

Recently, the problem of limited space in compact packaged electronics was thought [1] resolved by applying nanostructured zinc oxide coatings to bare aluminum and copper surfaces to make heat transfer at least as efficient as cooling fins. Coatings of zinc oxide having thicknesses of 50 - 150 nm were claimed to remove heat 4-10 X faster than bare surfaces. The multi-textured coating has a flower-like structure, the petals of which thought to promote bubble formation and rapid, efficient replenishment of active boiling sites. The encouraging heat transfer enhancements prompted the application [2] and award of US Patent.

However, the notion that porosity increases heat transfer finds basis in classical physics that excludes the size effect of QM. QM requires [3] the heat capacity of the atom to vanish in nanoscale coatings, and therefore the heat flow into the coating cannot be conserved by an increase in temperature. Because of QM, enhanced heat transfer in nanoscale coatings to take advantage of the increased area of porosity cannot occur. What this means is the increased heat transfer found [1] in pool-boiling had nothing to do with the porosity of the zinc oxide coating.

Instead, the enhanced heat transfer [1] is explained by conserving the heat into the coating by the QED induced creation of non-thermal EM radiation inside the nanoscale coating. The only QED requirement [3] is the RI of the coating is greater than that of the surroundings. For zinc oxide, the RI ~ 2, while the RI of water ~1.35 and aluminum and copper are about 1.5 and 1 respectively. The observed heat transfer enhancement for nanoscale zinc oxide coatings occurs as QED induced EM radiation created in the coating is absorbed in the water or substrate. At least half of the heat is directly absorbed in the water, the other half in the aluminum or copper substrates that lacking another heat loss path is eventually absorbed in the water. The heat transfer enhancement reported [1] is consistent with the QED requirement for the creation of EM radiation inside the coating. Porosity of the zinc oxide coating is inconsequential.

II. PURPOSE

In electronics, pool-boiling heat transfer by nanoscale coatings of zinc oxide avoids the complexity of cooling fins but requires a source of water that may be difficult to implement with sub-micron nanoelectronics. The purpose of this paper is to show how by simply applying a nanoscale zinc oxide coating to electronic circuit elements, the Joule heat is directly dissipated to the ambient air surroundings.

III. DESCRIPTION

QED radiation cooling is illustrated for an isolated coating in free space and an electronics application in Fig. 1. For the isolated coating, QM precludes the nanoscale thickness d from conserving the heat flux Q/A by an increase in temperature. Since the RI of the coating is greater than the vacuum, conservation proceeds by QED converting the heat flux to EM radiation that is absorbed in the surroundings, thereby cooling the coating.

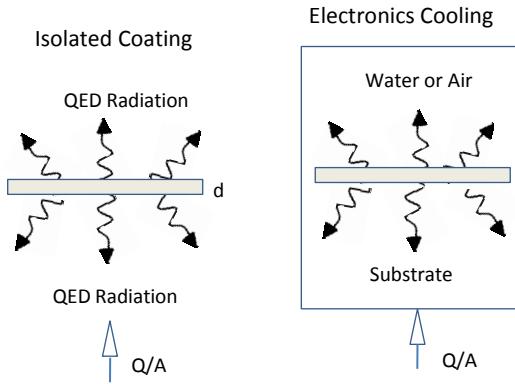


Fig. 1 QED Radiation Cooling
Isolated Coating and Electronics Application

In electronics, QED radiation is emitted as described for the isolated coating provided the RI of the coating is greater than that of the substrate and water or air surroundings. The Q/A heat flux generated from Joule heat in the circuit elements entering the coating from the substrate and dissipated by EM emission only to be absorbed in water or air surroundings.

IV. THEORY

A. QM Restrictions

Classically, the atoms in coatings have the heat capacity to increase in temperature upon the absorption of EM energy irrespective of coating thickness, i.e., there is no size effect in classical physics. QM differs in that the heat capacity of the atom depends on the thickness of the coating. A comparison of the thermal kT energy of the atom by classical physics and QM by the Einstein-Hopf relation [4] for the harmonic oscillator is shown in Fig. 2.

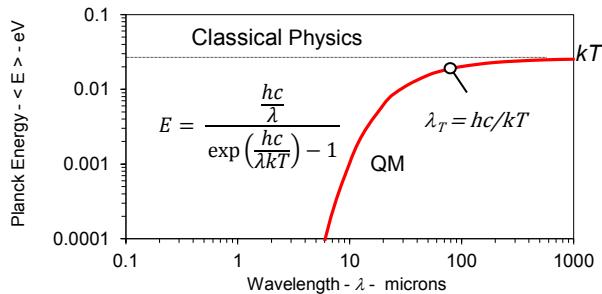


Fig. 2 Heat Capacity of the Atom at 300 K
 E is Planck energy, h Planck's constant, c speed of light,
 k Boltzmann's constant, T absolute temperature, and λ wavelength

QM allows the atom in macroscale coatings to have kT energy for $\lambda > \lambda_T$. At 300 K, $\lambda_T = 48$ microns. Conversely, atoms in coatings confined to wavelengths $\lambda < 6$ microns have $kT < 1/250$ eV while under nanoscale confinement $\lambda < 100$ nm the atom has no heat capacity to conserve absorbed EM energy by an increase in temperature.

B. TIR Confinement and QED

Unlike classical physics, QM precludes conservation of heat in coatings by an increase in temperature. Instead, the heat is conserved by the creation of non-thermal EM radiation by QED induced frequency up-conversion to the TIR frequency of the coating. TIR stands for total internal reflection.

TIR has a long history. In 1870, Tyndall showed light is trapped by TIR in the surface of a body if its RI is greater than that of the surroundings. Tyndall used water to show TIR confinement allowed light to be transmitted through curved tubes. TIR may confine any form of EM energy, although in electronics the confined EM energy is the Joule heat dissipated by the circuit elements.

TIR confinement requires Joule heat to be concentrated in the coating surface that is a natural consequence of having high surface to volume ratios, i.e., Joule heat is almost entirely concentrated in the coating surface. Under TIR confinement, QED induces the absorbed heat to undergo spontaneous conversion to surface EM radiation called QED induced radiation. However, TIR confinement is not permanent, sustaining itself only during the absorption of Joule heat, i.e., absent absorption there is no TIR confinement and QED radiation is not produced.

QED relies on complex mathematics as described by Feynman [5] although the underlying physics is simple, i.e., photons of wavelength λ are created by supplying EM energy to a QM box with sides separated by $\lambda/2$. In this way, QED conserves Joule heat by frequency up-conversion to the TIR resonance described by the thickness d of the coating. The Planck energy E of the QED radiation,

$$E = h\nu, \nu = \frac{c}{\lambda}, \lambda = 2nd \quad (1)$$

where, n is the RI of the coating.

V. ANALYSIS

A. Dispersion of QED Radiation with Wavelength

In pool-boiling, QED radiation in nanoscale coatings eventually dissipates all Q/A heat flux from the substrate by emission to the water surroundings. Fig. 1 shows that initially half of the QED radiation is reabsorbed in the substrate, but lacking another heat dissipation path is re-emitted successively back to the water. Depending on the coating thickness d , QED emission may occur from the EUV through the VIS to the IR. For pool-boiling [1] in water, the QED emission from $50 < d < 150$ nm zinc oxide coatings is in the UV-VIS. In general, the wavelength dispersion of QED radiation induced from the conservation of Joule heat is depicted for zinc oxide and silicon coatings in Fig. 3.

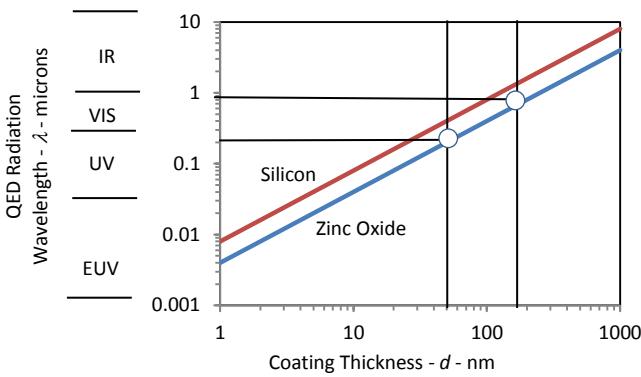


Fig. 3 QED Radiation Cooling
Wavelength of QED emission v. coating thickness

In water, all wavelengths except for the VIS are absorbed almost immediately while air is transparent for all wavelengths except for trace atmospheric gases. Absorption of QED radiation from electronics circuit elements cooled by air alone therefore occurs at adjacent solid surfaces, and if macroscopic, the surface temperatures do indeed increase. The QED radiation is successively emitted and absorbed by circuit elements throughout the electronic enclosure. Coating on the exterior enclosure surface allows the QED radiation to be finally dissipated to the ambient environment.

B. Comparison with Natural Convection

QED cooling converts heat into the coating to EM radiation of photons having wavelength λ that is totally dissipated to the surroundings.

$$Q_{QED} = \frac{hc}{\lambda} NA \quad (2)$$

where, H is an effective heat transfer coefficient. However, the coating and surroundings are required be at the same temperature as QM requires the heat capacity of the coating to vanish. No temperature difference between the coating and the surroundings is required in QED heat transfer.. Hence, the heat transfer H is infinite.

Natural convection differs. Heat transfer coefficients H in air vary between 10 and 100 W/m²-K. QED cooling having an infinite H is therefore is far more efficient than natural convection as all of the heat Q_{QED} is absorbed in the surroundings.

C. Absorption of QED Radiation in Air

The infinite heat transfer coefficient H assumes that the QED radiation is absorbed in a large region where the temperature T_{sur} of the surroundings does not increase. However, the QED radiation will increase the temperature of the air surroundings depending on the air absorption depth.

Absorption in air depending on the wavelength λ of QED radiation is a complex process. A simplified approach [6] is to assume Rayleigh scattering that although not an absorption process may be justified for narrow beams of QED radiation.

Over the range from the UV to the IR, the Rayleigh scattering cross-section $\sigma_R(\lambda)$ is,

$$\sigma_R(\lambda) = \frac{\sigma_{Ro}}{\lambda^4} \quad (4)$$

where, $\sigma_{Ro} = 4.4 \times 10^{-28} \text{ cm}^2$. The extinction coefficient due to Rayleigh scattering $\varepsilon_R(\lambda)$ is then given by,

$$\varepsilon_R(\lambda) = \sigma_R(\lambda) N_{air} \quad (5)$$

The intensity I of QED radiation is given by the increment dI over distance dS ,

$$dI = -I \varepsilon_R(\lambda) dS \quad (6)$$

Over a distance L , the intensity I is given in terms of the initial intensity I_o ,

$$\int_{I_o}^I \frac{dI}{I} = -\varepsilon_R(\lambda) \int_0^L dS \quad (7)$$

Combining,

$$\frac{I}{I_o} = \exp\left(-\frac{\sigma_{Ro}}{\lambda^4} N_{air} L\right) \quad (8)$$

The QED radiation intensity ($I/I_o - 1$) for $N_{air} = 2.4 \times 10^{19}$ molecules / cm³ at $L = 100$ cm is shown in Fig. 4. The QED intensity in nanoelectronics having L less than 20 cm is insignificantly reduced by air absorption. Hence, QED radiation in conventional and nano electronics is expected to occur at solid surfaces in the surroundings.

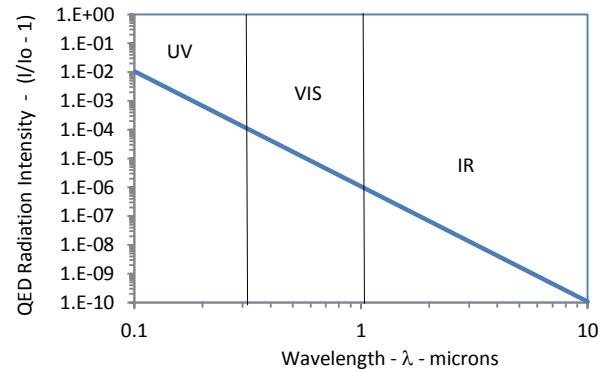


Fig. 4 QED Radiation Absorption in Air
Radiation Intensity v. Wavelength

VI. DISCUSSION

Cooling by QED radiation is not new, having been misinterpreted over the past half century in nanoscale films as reduced thermal conductivity or ballistic heat transfer because measured heat flow is lower than that predicted by the Fourier equation, brief summaries of which are as follows.

A. Thin Films

Today, the BTE is primarily directed to the steady state derivation of thickness dependent thermal conductivity of thin films, although the reduced conductivity of thin films has been known [7] for over 50 years. BTE stands for Boltzmann transport equation. Over this time, the Fourier heat conduction equation has failed to explain thickness dependent thermal conductivity. However, the BTE is recently [8, 9] claimed to explain reduced thin film conductivity.

Nevertheless, the BTE and Fourier solutions are questionable because of the heat balances assumed for the films. The problem is thin films emit QED radiation beyond the UV to the surroundings [10] that is not included as a loss in the heat balance, and therefore the thermal conductivity is concluded to be reduced from bulk. Alternatively, if the QED radiation loss is included in the balance, the conductivity remains at bulk. The exclusion of QED radiation from the heat balance is understandable as frequencies beyond the UV would normally not be observed during thin film experiments.

Paraphrasing the thin film experiments [8, 9] in terms of electronics cooling, the QED radiation actually cooled the films, but was mistakenly interpreted as a reduction in thermal conductivity. QED radiation dissipates Joule heat to the surroundings, and therefore there is no need to reduce the conductivity to explain lower heat flows.

B. Graphene Field-effect Transistors

Currently, the heat transfer analysis [11] of Joule heat in FETs is based on the Fourier diffusion equation. FET stands for Field-effect transistors. Classically, the graphene may lose heat by EM thermal BB radiation. BB stands for blackbody. However, BB radiation from the graphene at the peak temperature of 1000 K is negligible. Even at FET temperatures [12] of 2000 K, the BB radiated power remains an insignificant fraction of the Joule heat. Hence, the Joule heat is thought balanced solely by thermal conduction lateral to the graphene sheet into the SiO₂ substrate and underlying silicon layer.

The problem is the QED radiation loss required by QM is not included in the classical heat balance of the graphene, the omission [11, 12] leading to the conclusion that Joule heat produces temperatures from 1000 to 2000 K. However, if QED radiation is included in the heat balance, Joule heat does not increase the graphene temperature. By including QED radiation loss in the solution of Fourier's equation, the FET temperatures remain near ambient.

C. Quasi-ballistic Thermal Transport

Fourier theory of thermal transport is not valid at length scales smaller than the mean free path for the energy carriers in a material, which can be hundreds of nanometers in crystal line materials at room temperature. Instead, ballistic transfer is thought [13] to control heat transfer with the consequence that the heat flow away from a nanoscale hot spot is reduced by as much as 3X. Indeed, the Fourier equation over-predicts the heat flow. Alternatively, the thermal conductivity near the hot spot is reduced as described [8, 9] for thin films.

Again, the exclusion of QED radiation loss from the hot spot explains why the Fourier equation over-predicts the heat flow. By including QED radiation in the heat balance, the Fourier equation correctly yields a reduced heat flux. In effect, the beneficial cooling of the hot spot by QED radiation was interpreted to justify ballistic heat transfer.

D. Thermal Conductivity Spectroscopy

Ballistic heat transfer in heat conduction is thought [8-9, 11-13] to occur when phonon MFPs are comparable to the dimensions of nanoscale devices, the consequence of which is interpreted as the reduction in thermal conductivity or reduced heat flow instead of a beneficial cooling effect by QED radiation. MFP stands for mean free path. Moreover, first-principles calculations [14] show that MFPs of phonons relevant to thermal conductivity vary by more than 5 orders of magnitude, thereby accentuating the uncertainty of ballistic heat transfer instead of taking advantage of the cooling afforded by QED radiation.

To overcome the uncertainty in MFPs, a thermal spectroscopy technique is claimed [15] to measure MFPs over a wide range of length scales and materials. However, The technique is based on the false premise that the heat flux from a heat source will be lower than that predicted by Fourier's law when some phonon MFPs are longer than the hot spot dimensions. Experimental verification of the technique is limited to length scales of tens of microns, not nanometers. Again, QED radiation losses from the heat source are excluded from the ballistic heat transfer that if included would show the Fourier equation does indeed correctly predict the lower heat flow measured.

E. Non-diffusive Transport in Silicon Membranes

Deviations from the Fourier law are thought caused by phonon mediated-thermal conductivity. In silicon at room temperature, the majority of phonons have MFPs of about 43 nm, and therefore deviations from the classical Fourier equation are not expected at micron distances. Contrarily, a growing body of experiments shows micron sized structures far greater than the MFP of silicon no longer follow diffusive behavior, e.g., heat transport is not consistent with diffusion theory at 1 micron sized structures.

To investigate the validity of ballistic heat transfer at long MFPs, experiments [16] on 400 nm freestanding silicon membranes were conducted. By crossing two laser pulses on the membrane surface, an interference pattern was formed with a period defined by the angle between the beams. Absorption of laser light leads to a spatially periodic temperature profile, and the decay of this temperature grating by thermal transport is monitored by the diffraction of a probe laser beam.

Similar to reductions in thermal conductivity [8-9, 11-13, 15] observed in past experiments, the effective thermal conductivity is explained by the transition from a diffusive to a ballistic transport regime for micron sized MFPs far longer

than the 43 nm MFP for silicon. Instead of invalidating ballistic transfer theory, deviations from the Fourier law in phonon mediated thermal conductivity are stated [16] to occur at much larger distances than previously thought. Hence, we should change our way of thinking about ballistic heat transfer.

The interpretation here differs. The reduced thermal conductivity of silicon is once again erroneous as QED induced radiation was excluded from the heat transfer analysis by the Fourier equation. From (1), the QED radiation emitted from the 400 nm silicon membrane having a RI of $n = 3.2$ is in the NIR at 2.6 microns as shown in Fig. 4. Confirmatory measurements may be made with IR spectroscopy.

VII. CONCLUSIONS

The significant enhancement in pool-boiling heat transfer found by coating aluminum and copper with 50-150 nm zinc oxide is not caused by the porosity of the coating, but rather by the QED radiation created within the coating that upon emission is absorbed in the water coolant.

QED radiation is produced because QM precludes the coating atoms from having the heat capacity to conserve the heat supplied by an increase in temperature. Because of QM, QED induces the heat to be conserved by creating EM radiation at the frequency of the TIR confinement provided the RI of the coating is greater than the substrate. The QED radiation from 50-150 nm zinc oxide coatings is in the UV to VIS from 0.2 to 0.6 microns and would not be observed in the turbulence of pool-boiling for the water coolant.

With regard to electronics cooling, pool-boiling with water coolant is superseded by simply applying the 50-150 nm zinc oxide coating to the surface of circuit elements. Joule heat is then totally dissipated by UV-VIS radiation to the air surroundings. Although UV absorbent, air is transparent in the VIS, and therefore the QED radiation is generally absorbed in solid surfaces, the process continuing within the electronic enclosure. Coating the enclosure dissipates all Joule heat to the ambient surroundings.

QED cooling in air is far more efficient than natural convection. In fact, QM precludes a temperature difference between the coating and the surroundings. Hence, the effective heat transfer coefficient is infinite compared to values of 10 to 100 W / m²·K for natural convection.

Ambient air is virtually transparent to QED radiation having wavelengths from the UV to the IR. For an air column having a length of 100 cm, the extinction of QED radiation is insignificant. Most electronics having enclosures less than 30 cm therefore dissipate QED radiation by absorption in the enclosure walls. By coating the exterior enclosure, the heat removal is easily managed.

QED radiation is not new having been observed for many years, but the beneficial effect of cooling has been misinterpreted as reduced thermal conductivity based on ballistic heat transfer or reduced heat flow from that predicted by the Fourier equation. By including QED radiation as a loss in the heat balance of nanostructures, electronics circuit elements or otherwise, the beneficial effects of cooling may be fully realized.

REFERENCES

- [1] T. J. Hendricks, S. Krishnan, C. Choi, C-H Chang, and B. Paul, "Enhancement of pool-boiling heat transfer using nanostructured surfaces on aluminum and copper," International Journal Heat and Mass Transfer, vol. 53, pp. 3357–3365, 2010.
- [2] T. J. Hendricks, et al., "System and Method for enhanced heat transfer using nanoporous textured surfaces. US Patent 20110203772A1, Published Aug. 25, 2011.
- [3] T. Prevenslik, "Heat Transfer in Nanoelectronics by Quantum Mechanics," ASME InterPACK, Burlingame, CA, USA, July 16-18, 2013.
- [4] A. Einstein and L. Hopf, "Statistische Untersuchung der Bewegung eines Resonators in einem Strahlungsfeld," Ann. Physik, vol. 33, pp. 1105-1120, 1910.
- [5] R. Feynman, QED: The Strange Theory of Light and Matter. Princeton University Press, 1985.
- [6] F. Trager, Springer Handbook of Lasers and Optics, Chapter 19, Radiation and Optics in the Atmosphere, pp. 1166-1167. ISBN: 978-3-642-19408-5
- [7] P. G. Kelemen, "Pulse Method for the Measurement of the Thermal Conductivity of Thin Films," Thin Solid Films, vol. 36, pp. 199-203, 1976.
- [8] W. Liu, Y. Yang, and M. Asheghi, "Thermal and Electrical Characterization and Modeling of Thin Copper Layers," Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems IITHERM, San Diego, 2006.
- [9] M. Aseghi and W. Liu, "Microscale heat transfer," Electronics Cooling, February, 2007.
- [10] T. Prevenslik, "Heat Transfer in Thin Films," Third Inter. Conf. on Quantum, Nano and Micro Technologies, ICQNM, Cancun, February 1-7, 2009.
- [11] M. Freitag, et al., "Energy Dissipation in Graphene Field-Effect Transistors," Nano Lett., vol. 9, pp. 1883 – 1888, 2009.
- [12] S. Berciaud, M. Y. Han, K. F. Mak, L. E. Brus, P. Kim, and T. F. Heinz, "Electron and Optical Phonon Temperatures in Electrically Biased Graphene," PRL, 104, pp. 227401, 2010.
- [13] M. E. Siemens, et al., "Quasi-ballistic thermal transport from nanoscale interfaces observed using ultrafast coherent soft X-ray beams," Nature Materials, vol. 9, pp. 26-30, 2010.
- [14] A. Ward and D. A. Broido, "Intrinsic phonon relaxation times from first-principles studies of the thermal conductivities of Si and Ge," Phys. Rev. B 81, 085205, 2010.
- [15] A. J. Minnich, et al., "Thermal Conductivity Spectroscopy Technique to Measure Phonon Mean Free Paths." PRL vol. 107, 095901, 2011.
- [16] J. A. Johnson, et al., "Direct Measurement of Room-Temperature Nondiffusive Thermal Transport Over Micron Distances in a Silicon Membrane," PRL, vol. 110, 025901, 2013.