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Heat Dissipation in GaN based Power Electronics

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Gallium Nitride (GaN) possesses superior electronic properties for RF power electronics that play critical rolls in various wireless communication technologies and military applications (1). Heat generated as a byproduct of operation in these devices, increases their operating temperature and degrades their performance and lifetime. We will discuss thermal transport in GaN based devices, broadly addressing the impact of heat source dimensions, film thicknesses, interfaces, and defects.

Contemporary GaN HEMTs utilize a high electron mobility 2-dimensional electron gas (2-DEG) that exists at the interface of AlGaN and GaN thin films. SiC or sapphire substrates with AlN nucleation layers are the platform for epitaxial growth of the HEMT heterostructure, because GaN and AlN substrates are not economically viable. Joule heat generated in the 2-DEG must pass through a series of thermal resistances before its ultimate disposition to the environment. While package-level thermal management strategies have been called upon to mitigate these concerns, substantial thermal resistance exists within the device itself (2). The size of the devices and the presence of films and interfaces leads to thermal resistances that are higher than expected.

Previous experimental studies of thermal conductivity (k) have shown that single crystal GaN, AlN, and SiC have very high k that is dominated by phonons. Room temperature values of k exceed 200 W/m-K in GaN (3) and AlN (4) and are reported as high as 490 W/m-K in SiC (5). Yet achievement of such high values is more challenging in practice, when the mean free paths (MFPs) of phonons are reduced by the presence of interfaces, grain boundaries, and dislocations that limit the MFP of phonons (6). Since the distribution of MFPs spans nearly four orders-of-magnitude, some phonons remain diffusive, while others are scattered by boundaries and defects.

To explain k as a function of phonon MFP, the thermal conductivity accumulation function is defined as,

$$k_{accum}\left(l^{*}\right)=\sum_{s}\int_{0}^{l^{*}}\frac{1}{3}C\left(l\right)v\left(l\right)l\,dl$$

where l is the phonon MFP, v is the phonon group velocity, C is the volumetric heat capacity per unit phonon MFP, and s indexes the polarization of phonons. When l^* is set to infinity this predicts the bulk k because all phonon MFPs are included. The value of k_{accum} when l^* is set to the film thickness or defect spacing can be used as an estimate of the thermal conductivity suppression when some MFPs are reduced. Due to non-diffusive effects, it has also been shown that heat sources with dimensions d perceive a reduced k that can be approximated as k_{accum} when $l^*=d$ *(7)*.

We have made direct experimental measurements of k_{accum} in GaN, AlN, and SiC using a novel technique known as broadband frequency domain thermoreflectance (8). Here we use high frequency surface temperature modulation that generates non-diffusive phonon transport to probe the phonon mean free path spectra of GaN, AlN, and 4H-SiC at temperatures near 80K, 150K, 300K, and 400K. In stark contrast to sub-100 nm estimates of the average phonon MFP based on kinetic theory, we find that phonons with MFPs greater than 1000±200 nm, 2500±800 nm, and 4200±850 nm contribute 50% of the bulk thermal conductivity of GaN, AlN, and 4H-SiC near room temperature. Hence, localized suppression of k will increase the operating temperature of HEMTs, built from thin, highly defective films, and have localized small heat sources.

Another consideration is the effect of interfaces, which induce increased thermal resistance as phonons transmit from one material to another. Our prior studies on similar GaN-based LED structures show that the AlN-substrate interface is the dominant thermal resistance in the system (9). New data, shown in Figure 1, prove that interface roughness plays a significant role in reducing the thermal boundary resistance (TBR). Here we plot the thermal resistance (*thermal conductivity/thickness=k/L*) of AlN films vs. film thickness for AlN on mechanically polished SiC (MP; RMS roughness=1.2nm), chemomechanically polished SiC (CMP; RMS roughness=0.2nm), and sapphire (RMS roughness=0.2nm) substrates. Since the data are only weak functions of film thickness, we conclude that thermal boundary resistance (TBR) dominates over film resistance. The TBR of AlN/CMP-SiC is ~10 times lower than that of AlN/MP-SiC, regardless of whether the AlN film is grown by organometallic vapor phase epitaxy (industry standard) or plasma vapor deposition. After subtracting the TBR of the top contact, we estimate that the TBR of the AlN/CMP-SiC interface is 5.1±2.8 m^2-K/GW—equal to 1450 nm of single crystal AlN!

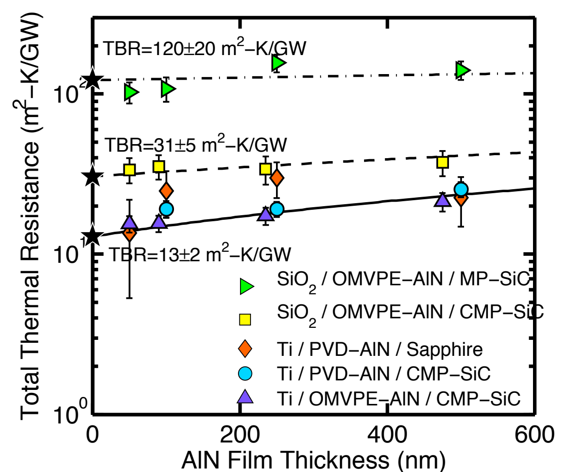

Figure 1. Thermal boundary resistance of AlN films vs. film thickness. Legend indicates top and bottom contacts.

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