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CARBON NANOTUBE ARRAY THERMAL INTERFACES ON CHEMICAL VAPOR DEPOSITED DIAMOND

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ABSTRACT

Carbon nanotube (CNT) arrays have been directly synthesized on plasma-enhanced chemical vapor deposited diamond films in the same growth chamber. The diamond films were grown using a bias-enhanced nucleation technique that produces relatively smooth and flat films. The thermal resistances of the CNT array/diamond film interface were measured using a photoacoustic technique to be approximately 12 mm²·K/W at moderate pressures.

NOMENCLATURE

R	thermal resistance, mm²·K/W

Subscripts

CNT array	CNT array
CNT-silver	free CNT tips to silver
DLC	nucleation layer
DLC-PD	nucleation/polycrystalline diamond interface
PD	polycrystalline diamond layer
PD-CNT interface	CNT array/diamond growth substrate interface
silicon-DLC	silicon/nucleation layer interface
total	complete CNT array/diamond film interface

INTRODUCTION

Motivated by the growing thermal management needs of the semiconductor industry, carbon nanotube (CNT) arrays have been the focus of recent attention for their ability to achieve low thermal resistance in an interface [1,2,3,4,5]. CNT array interfaces are dry and removable, and have been demonstrated to attain resistances less than 10 mm²K/W [4,5], which exceeds the performance of state-of-the-art thermal interface materials. In fact, CNT thermal interfaces with arrays grown on both sides of the interface have achieved resistances similar to a soldered joint [4]. However, CNTs may not be suitable for some applications because they are electrically conductive. Chemical vapor deposited (CVD) diamond films have the potential to improve heat transfer from high-density microelectronics while providing good electrical insulation [6]. The high in-plane and cross-plane thermal conductivities of diamond make it particularly effective in spreading heat away from hot spots to a heat sink.

A single plasma-enhanced CVD (PE-CVD) growth chamber has been used to synthesize diamond films coated with dense, vertically oriented CNT arrays. The diamond provides electrical insulation and effectively spreads heat over the substrate, while the CNTs act to bridge the interface gaps, efficiently delivering heat to a sink. A bias-enhanced nucleation (BEN) technique was used that produced relatively smooth and flat diamond films, which are necessary for good thermal interface performance. The thermal interface resistances of the CNT array/diamond film interface, R_{total}, are measured as a function of pressure using a photoacoustic (PA) technique, and they compare favorably with previous results [2,3,4].

SYNTHESIS

Diamond films were synthesized on polished silicon wafers using a two step process, similar to a previous study [6], in which a nucleation layer of diamond-like carbon (DLC) was deposited via BEN and then conditions were changed to allow for the growth of polycrystalline diamond (PD). Nucleation was carried out in a 300 W plasma and at a constant DC bias of -250 V. Diamond growth was carried out in a 1200 W plasma with no applied bias. Methane and hydrogen were the reactive gases during both growth steps. Nucleation was carried out for 15 minutes in a 200:10 methane to hydrogen ratio, and diamond growth was carried out for 4 hours in a 200:2 ratio.

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The columnar gain structure, characteristic of PD, can be clearly observed in Figure 1(a). The thickness of the complete diamond film is approximately 0.5 μm as determined from scanning electron microscope (SEM) images.

The CNT arrays were synthesized on the diamond films using a trilayer catalyst configuration (30 nm Ti/10 nm Al/4 nm Fe) and the same growth conditions used in a previous study [4]. Growth was carried out at 900 °C in a 200 W plasma, and a 50:10 methane to hydrogen gas ratio was used. Figure 1(b) contains an SEM image of the CNT array on the diamond film after PA testing and removal from the interface. The CNT array is approximately 10 μm in height (~ 12 μm before PA testing). The CNT diameters range from 5 to 50 nm, and the average CNT diameter is approximately 30 nm. The CNT density is estimated to be on the order of 10^8 CNTs/mm^2.

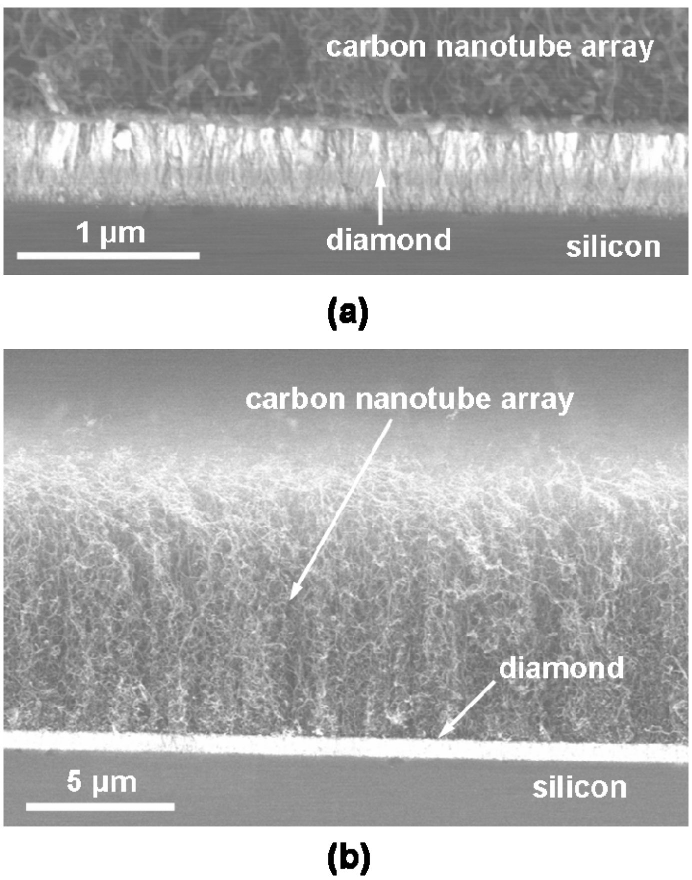

Figure 1. (a) High magnification (x30k) image of the diamond film. (b) Lower magnification (x6k) image that illustrates the full height of the CNT array.

RESULTS

The complete CNT array/diamond interface contains several local resistances. The diamond films grown on silicon consist of two layers (PD and nucleation) and two associated interfaces. Thermal conduction through the complete diamond structures has been studied [6], and total resistances were measured to be approximately two orders of magnitude less than previously measured CNT interface resistances [4].

The inclusion of CNT arrays grown directly on the diamond films adds three additional local resistances to the interface: CNT to growth substrate ($R_{PD\text{-}CNT}$), free CNT tips to opposing substrate ($R_{CNT\text{-}silver}$), and the intrinsic resistance of the CNT array ($R_{CNT\ array}$). Past work has shown that the free CNT tips to opposing substrate interface is the largest local resistance and dominates the resistance of one-sided (arrays grown on only one side of the interface) CNT interfaces [4]; for the CNT array/diamond interface, this resistance ($R_{CNT\text{-}silver}$) is dominant as well. A resistive network for the CNT array/diamond film interface is illustrated in Figure 2.

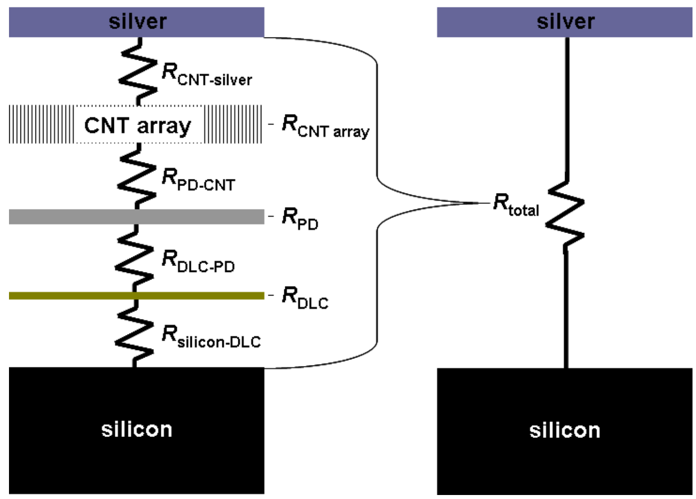

Figure 2. Resistive network for the CNT array/diamond film interface.

The room-temperature thermal interface resistance of the complete CNT array/diamond film interface, R_{total}, was measured using the PA technique in a pressure range characteristic of microelectronics packaging applications, and the results are illustrated in Figure 3. In PA measurements, a heating source (normally a laser beam) is periodically irradiated on a sample surface. The acoustic response of the gas above the sample is measured and related to the thermal properties of the sample. Reference 4 provides detailed description of the PA technique used in this study. Similar to previous work [4], silver foil was used as the top substrate to allow for maximum measurement sensitivity. After testing, the interface was separated, and the CNT array remained firmly attached to the diamond surface, indicating that the CNT array was well adhered to the diamond.

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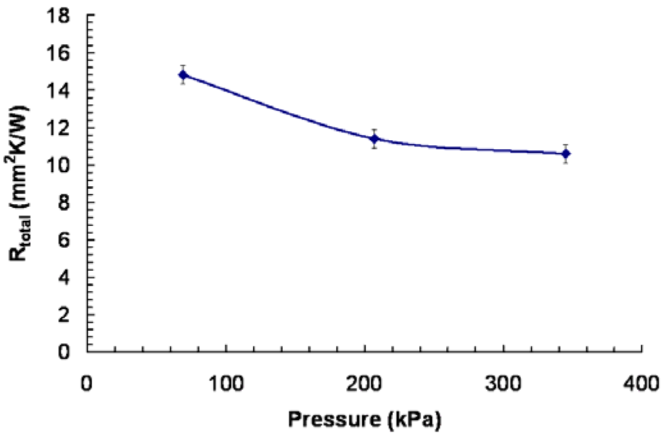

Figure 3. Thermal resistance of the complete CNT array/diamond film interface as a function of pressure.

As illustrated in Figure 3 the CNT array/diamond film interface achieves resistance values near 12 $mm^2 \cdot K/W$ in the test pressure range. One-sided CNT array interfaces directly synthesized on polished silicon have been reported to range from 16 to 20 $mm^2 \cdot K/W$ at similar pressures [2,3,4]; hence, the current interface structure compares favorably.

In Figure 3, it can be observed that the resistance of the CNT array/diamond film interface only changes slightly with increased test pressure. We attribute this behavior to the CNT array having sufficient height (to overcome surface roughness) and density (which limits the arrays ability to further compress) such that near maximum contact is created in the interface upon initial loading.

CONCLUSIONS

The room-temperature thermal resistance of a CNT array/diamond film interface was measured to achieve low resistances near 12 $mm^2 \cdot K/W$ with little pressure variation in the test range, which compares very favorably with previous results [4] and state-of-the-art thermal interface materials. Additionally, the thermal resistance due to the presence of the thin, dielectric diamond layer [6] is negligible in comparison to the total interface resistance, which is dominated by the local resistance at the free CNT array tips [4].

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