

Thickness dependence of the electrical characteristics of chemical vapor deposited diamond films

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The electrical characteristics of chemically vapor deposited (CVD) diamond films were measured as a function of film thickness. The samples studied were polycrystalline with the average grain size increasing from approximately 1 μm on the substrate side to approximately 30 μm on the growth surface for the thickest sample. Using time-resolved transient photoconductivity and charged-particle induced conductivity, the collection distance (d) that a free carrier drifts under the influence of an applied electric field was measured. Our data indicate that there is a gradient in the collection distance through the material. This gradient in electrical properties has implications for electronic uses of CVD diamond.

For high speed, high power, and harsh environment applications, diamond is potentially unmatched as a semiconductor for electronic applications.^{1,2} The small size of single-crystal natural diamonds and the poorer quality of polycrystalline chemically vapor deposited (CVD) diamond has limited the development of diamond electronic devices. However, recent improvements in the electrical characteristics of CVD diamond films have been reported, with polycrystalline diamond displaying mobilities equal to that measured in natural, single-crystal IIa diamonds.³ In this letter the improved electrical performance is linked to larger grain sizes. It is observed that both the electrical properties and the grain size vary linearly with film thickness.

CVD diamond typically grows with a columnar structure. The substrate side begins with small grains which grow with material thickness as the film gains a texture from the preferred growth of certain crystal orientations. Samples for this study were grown by two different CVD techniques and varied in their optical properties from opaque to translucent.⁴ In this study the electrical characteristics of diamond were studied with two techniques, photo-induced and particle-induced conductivity. As performed, photoexcitation results in conduction across the grains and can be used to study the electrical properties of the growth surface where the grains are the largest. Particle excitation results in conduction through the thickness of the sample and is a measure of the bulk collection distance in this direction.

The basic photo- or particle-excited conductor consists of a piece of semiconductor with two ohmic contacts. In our experiments, the contacts are on the same surface for the photoexcitation and on opposite faces for the particle excitation. When energy from light or an ionizing particle is ab-

sorbed within the material, free carriers are created and the conductivity increases. The free electrons and holes drift in the applied electric field inducing a current or charge on the electrodes which can be measured. After excitation of the diamond, the measured charge, Q , is related to the amount of charge generated in the material, Q_{ion} , the average mobility, μ , the average carrier lifetime, τ , the distance between the contacts, l , and the distance the electrons and holes move apart, d , by

$$Q = \left(\frac{Q_{\text{ion}}}{l} \right) \mu \tau E = Q_{\text{ion}} \left(\frac{d}{l} \right).$$

Both techniques measure the mean-free path of free carriers (d) drifting in an electric field. This quantity is an important parameter for applications, such as photodetectors, and as seen from the equation, is proportional to the mobility-lifetime product of the free carriers. The mobility and lifetime can be determined separately from the collection distance using photoconductivity measurements.

The photoconductivity experiments were performed using excitation by a frequency tripled Nd-YAG laser (6.1 eV). Laser pulses contained up to 100 μJ , and were capable of generating carrier densities from 10^{14} to 10^{18} cm^{-3} , at a depth of less than 2 μm from the surface. By using the charge collected as a result of each pulse, the $\mu\tau$ product of the material was measured. Since the energy of the excitation source is just above the band gap this technique probes only the first few microns of the material. The particle-induced conductivity experiments were performed using a radioactive source (^{90}Sr) and a scintillation counter behind the diamond to serve as the trigger. This source produces electrons with a β -spectrum up to an end point of 2.28 MeV. In this case, the average energy to create an electron-hole pair in diamond is $\sim 13 \text{ eV/pair}$.⁵ Above an energy of $\sim 1 \text{ MeV}$ these electrons fully traverse the material creating 36 electron-hole pairs per

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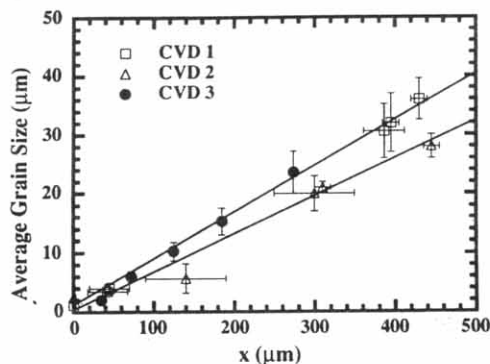


FIG. 1. The average grain size of the growth surface increases linearly with the surface position of the sample. Data for three sets of samples are shown; sets 1 and 2 are grown by arc-jet CVD and set 3 is grown by microwave CVD. Lines are drawn to guide the eye.

micron of diamond traversed producing a density of $\sim 10^{13}$ pairs cm^{-3} . At these energies, this technique averages the collection distance over the bulk of the material. As a check, samples were measured with the particles incident on either the top or bottom surface. Identical results were obtained which verify that the measured collection distance is averaged through the thickness and not weighted toward either surface.

Two approaches were used to study property variation with position of the diamond top surface with respect to the original back surface (substrate side). One approach uses thick diamond samples (500 μm) cut from the same wafer which are thinned by polishing either or both surfaces to different final thicknesses. The other approach involved growing a series of films to different thicknesses using identical growth conditions. Three sets of samples were studied: sets 1 and 2 were examined by the first approach, set 3 was examined by the second approach. Particle-induced conductivity measurements were done on sample sets 1 and 2, while photoconductivity measurements were performed on sets 2 and 3 and one sample from set 1. Figure 1 is a plot of the average grain size of the surface layer versus the distance of the diamond surface from the substrate interface for these three sets of samples. This distance will subsequently be referred to as the *position* of the surface. The average grain size was determined from scanning electron microscope (SEM) micrographs by counting the number of crystallites that fill a given area. A linear relation is observed between the average grain size and the surface position for each type of sample with no saturation up to positions of 500 μm . This close relationship between grain size and position means that any observed dependence on position also implies a correlation with grain size.

The surface collection distance, d_s , as measured by photoinduced conductivity, is plotted in Fig. 2 as a function of the bulk collection distance, d_B , as measured by particle-induced conductivity, at a fixed electric field of 10 kV/cm for several samples. These samples were grown by both arc-jet and microwave CVD and some were thinned by the procedures described above. The striking feature of these data is that the surface measurements (y axis) are twice that of the

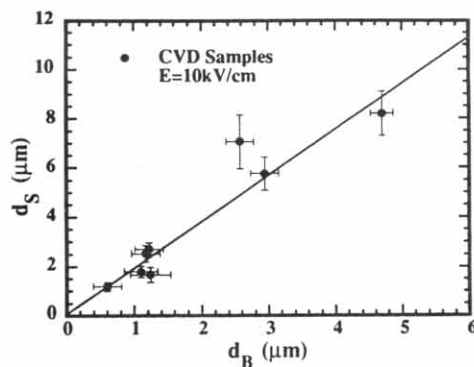


FIG. 2. Comparison of the bulk collection distance and the surface collection distance for several samples grown by both arc-jet CVD and microwave CVD. The line through the data is a least-squares fit with a slope of 1.88 indicating that the collection distance at the growth surface is about twice the bulk collection distance.

bulk measurements (x axis) regardless of the growth technique or post-deposition processing. If the collection distance increased linearly from the substrate side to the growth side, the slope of this line would be 2.00 and the collection distance at the growth surface would be twice the bulk collection distance. A linear fit to the data indicates an intercept of 0.01 μm and a slope of 1.88 ± 0.27 , consistent with this premise. In a previous study in single-crystal natural IIa diamond the bulk and surface values were equal, indicating a uniform collection distance throughout that material.⁶

The surface collection distance, d_s , at the growth surface is plotted in Fig. 3 as a function of position for a fixed electric field of 10 kV/cm for sample sets 2 and 3. For comparison the surface collection distance for sample set 1 was deduced from the bulk data according to the fit in Fig. 2 and plotted on the same graph as a function of position. The CVD diamonds exhibit a rise in collection distance with surface position, which was due primarily to an increase in mobility with thickness and grain size as identified by photoconductivity measurements. This result indicates that the collection distance increases as the sample grows thicker and as the grains grow larger. These results show that the relationship between the collection distance and surface position

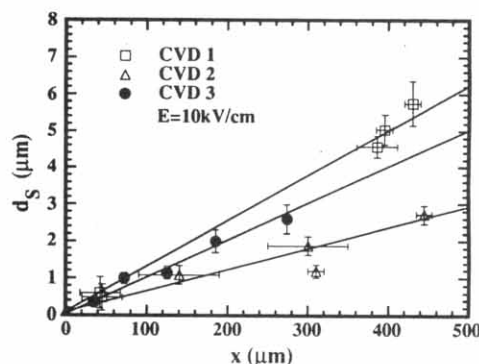


FIG. 3. The surface collection distance increases linearly with position for sample set 3. The bulk collection distance of sample sets 1 and 2 is doubled and included for comparison.

follows a similar trend for different sets of samples, but the slopes are not identical. This is consistent with a linear change in the collection distance with surface position, suggesting that the bulk properties are to first order the average of the growth surface results. A similar relationship between collection distance and surface position has been recently observed in diamond films that were optimized for electrical properties, which had even higher collection distances.⁷

In summary, we have measured the electrical properties of a large number of CVD diamond films. A distinct gradient in material quality has been observed, progressing from the substrate side to the growth side. The improvement is essentially linear, up to the film thicknesses that we have examined (500 μm). This improvement in electrical properties is likely a consequence of lower defect densities and increased grain size as a function of thickness. Within these samples the collection distance is small compared to the dimensions of a single grain. However, the collection distance appears to correlate with grain size. Insufficient evidence exists to explain this conclusively, but possibly there are intragrain defects whose density decreases as the film grows thicker, leading to a correlation with grain size. Cathodoluminescence suggests that the dislocation density in flame-grown polycrystalline diamond films decreases from the nucleation side to the growth side.⁸ Also, similar gradients have been observed in polycrystalline silicon.⁹ Depending on the electrical application, it may be important to take this nonuniformity

in material quality into consideration. For example, in applications where the average electrical properties through the diamond film are important, removal of some of the smaller grain material near the substrate side would improve the average behavior.

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