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Development of an extremely thin-diamond window for terahertz traveling wave tubes

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A B S T R A C T

This paper describes the design and fabrication of an extremely thin-diamond window for terahertz traveling wave tubes (THz TWTs). To reinforce the mechanical properties of the micro-crystalline diamond (MCD) incorporated with ultra-nano-crystalline diamond (UNCD), a seven-layered composite diamond having a total thickness of 60 μm has been fabricated and studied. SEM studies showed that UNCD growth on MCD resulted in surface roughness improvement via smoothing sharp corners and straight edges as well as filling in valleys of MCD grains. Further comparison studies of the same thickness samples demonstrated that the roughness for the composites were ~25–50% lower than those of the MDCs, depending on the number of UNCD layers. More importantly, seams or gaps resulting from irregularly shaped MCD grains were found to be terminated by UNCD growth, which is believed to attribute to the lateral growth mechanism of UNCD. The seven-layered composite diamond film was cut into window disks without lapping and polishing, which were then made into window assemblies. The mechanical testing of the window assembly showed no occurrence of window cracking or other damages due to the mechanical stress from pressure difference, while leak tests found no apparent air leakage resulting from the composite material. These testing results show such a thin composite diamond possesses adequate mechanical properties for the application of THz wave TWT windows. This work provides a novel approach for the fabrication of extremely thin-diamond windows for THz TWTs.

1. Introduction

Terahertz (THz) wave is known as a gap between microwave and far infrared, defined as a frequency band from 300 to 3000 GHz. In the past ten years, researchers have become more and more interested in developing THz wave sources due to their potential applications, such as THz spectroscopy [1,2], imaging [3,4], wireless communication [5], security inspection [6] and Radars [7,8]. Among several types of THz sources including solid state and photo-electron devices [6–8], vacuum microwave devices, such as THz traveling wave tubes (TWTs), are considered to be promising in terms of their capability to offer relatively high radiation power [9–11]. As the operating frequencies of the vacuum microwave device approach THz region, characteristic dimensions of the components and parts become much smaller, making the fabrication technique rather challenging. One of the key components is the air-tight window assemblies. To achieve effective transmission of THz wave, the designed thickness of the window could be down to tens of μm. To endure mechanical stress from an atmospheric pressure difference, the window must have adequate mechanical strength as well as thickness. The minimum thickness Lmin for a window disk is correlated to mechanical strength Fs measured as fracture strength, given by [12].

$$\mathrm{Lmin} = 0.55\mathrm{D}(\Delta\mathrm{p}\cdot\mathrm{SF}/\mathrm{Fs})^{1/2}$$

where, D is the diameter of the window disk, Δp is the pressure difference between two sides, and SF is the safety factor. Inserting D = 5 mm, Δp = 1 bar, SF = 4, and Fs = 500 MPa-usually for a polycrystalline diamond (PCD, also known as microcrystalline diamond-MCD), a minimum thickness Lmin of 78 μm is obtained. For other commonly used dielectric materials such as sapphire and beryllium oxide, calculated values of Lmin would be much larger due to their lower mechanical strength. Even for diamond material, the window thickness designed for the minimum reflection in a THz TWT could be thinner than 78 μm, depending on the operation frequency. For example, Kimura et al. utilized a 76 μm-thick single-crystalline diamond (SCD) window with a diameter of 1.4 mm in their 220 GHz TWTs [13]. Currently, it seems that SCD is becoming a popular option for THz TWT windows since there are hardly other alternatives in this case. Tucek et al. also employed SCD windows in their much higher frequency TWTs [10,11]. Currently the cost of such a synthetic material, however,

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is high mainly due to low fabrication yield. On the other hand, though MCD can be deposited with large areas- > 4 in. in diameter, it is no longer applicable to such thin windows due to inadequate mechanical strength and vacuum tightness. Therefore, we previously made a preliminary study on a composite diamond of MCD with ultra-nanocrystalline diamond (UNCD) to overcome the above challenges, and demonstrated 100 μm-thick composite diamond windows for a short-mm wave TWT [14].

This paper presents a further study on composite diamonds aiming at THz wave TWT windows. To extend the operating frequency of the TWT window into THz region, a 60 μm-thick composite diamond with multi-layered UNCD has been developed and made into TWT window assemblies. The mechanical and air tightness testing results will be presented and discussed in Section 3. This work provides a novel method for fabricating extremely thin (< 100 μm) diamond windows for THz TWTs.

2. Experimental procedures

2.1. Design of multi-layered composite diamond films

In design of a THz TWT window assembly, both RF performance and mechanical properties must be taken into consideration. As mentioned in Section 1, the current major issue for the THz TWT window made of microwave plasma chemical vapor deposited MCDs is the mechanical properties, which is the target to be tackled in this work.

To reinforce the mechanical properties of the composite diamond film, including mechanical strength, air-tightness and surface roughness, a multi-layered diamond structure was designed, based on previous findings discussed in Subsection 3.2 of Section 3. Fig. 1 illustrates a 60 μm-thick composite diamond, which has four layers of UNCD and three layers of MCD with the thickness of each layer from bottom to top: 3 μm (UNCD), 17 μm (MCD), 1 μm (UNCD), 17 μm (MCD), 1 μm (UNCD), 17 μm (MCD) and 4 μm (UNCD). Based on the findings concerning transmission loss of UNCD [14,15], the total thickness of UNCD layers was minimized to about 10 μm.

2.2. Fabrication of multi-layered composite diamond films

Diamond films were produced on a N-type Si(100) wafer using a 6 kW, 2.45 GHz microwave plasma CVD (MPCVD) reactor [16]. Fabrication processes of MCD and UNCD have been reported in our previous paper [14]. Briefly, MCD films were prepared by a conventional H2/CH4 reaction gas mixture, whereas UNCD was deposited in a Ar-rich plasma with a small amount of CH4 and H2. Process transition between MCD and UNCD proceeded without turning plasma off. The growth rate for both MCD and UNCD was ~1 μm/h.

Fig. 2 gives an optical photo of three ∅ 40 mm × 60 μm diamond wafers: (a) pure MCD, (b) 1 μm UNCD over-layered composite, and (c) seven layered-composite diamond with the structure illustrated in Fig. 1. Unfortunately, the pure MCD was cracked during the etching process of Si, showing a fragile nature, whereas other two composites are intact.

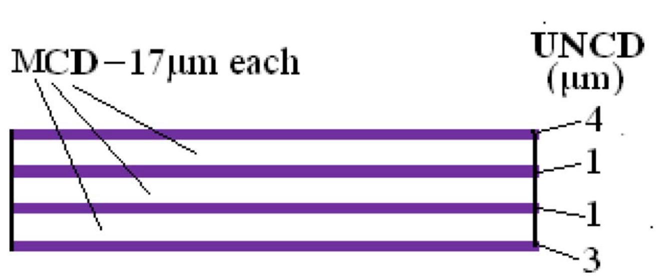

Fig. 1. A schematic diagram of the seven-layered-composite diamond with total thickness of 60 μm designed for THz TWT windows.

2.3. Sample preparation and testing

For the purpose of studies, apart from the above mentioned three types of diamonds, a number of composites with various UNCD layers and pure MCDs with different thickness were prepared. It should be mentioned that all the "as grown" diamond films were cut into window disks or test samples with no lapping or polishing.

3. Results and discussion

3.1. Surface smooth effect of UNCD growth on MCD

In our previous work, it was found from top view SEM images that MCD surface became smoothened as the sharp corners and straight edges disappeared gradually with the growing UNCD. To get more insight into the effect of UNCD growth on surface morphology of MCD, more studies have been conducted.

First, SEM images of two 60 μm-thick diamond samples, i.e. a pure MCD and a 4 μm UNCD-overlayered composite were taken with the samples tilted at 45°. It can be seen by comparison of these two images shown in Fig. 3 that the original corners and edges of polycrystalline grains are clearly smoothed following the growth of 4 μm UNCD, leaving grains in hillock shape.

Second, cross-section SEM studies of a 1 μm UNCD-overlayered composite were conducted in order to understand the possible effect of UNCD growth on MCD morphology in areas of valleys and gaps. Fig. 4 gives two cross-section SEM images taken from "V" shaped regions. It can be seen that two MCD valleys with angles of about 50° and 80° respectively are filled in with 1 μm UNCD, resulting in much widened angles above them. This indicates that surface roughness of the MCD can be further improved by filling-in process during the growth of UNCD. It is also interesting to note the manner of growing UNCD in the valleys. Both images show that UNCDs grow from the side walls of the MCD valleys towards each other till they meet.

Third, to gain more information on the improvement in surface smoothness of the composite film, a contour graph (Taylor Hobson PGI-400) was employed to measure roughness average for a number of samples. Fig. 5 gives the values of roughness average with measurement error around ± 0.025 μm as a function of thickness of diamond samples, including pure MCDs and composite ones denoted by squares and diamonds respectively. Generally speaking, the surface roughness for both pure MCDs and composites tends to increase with the increased film thickness since the grain size becomes large. However, all the values for the composites are ~25–50% lower than those of the MDCs, which confirm the above SEM observation. It is also noticed that the more UNCD layers there are, the lower the roughness becomes. In practice, the number of UNCD layers are limited to the total UNCD thickness of ≤ 10 μm as to reduce transmission loss from sp2 carbon atoms in UNCD [14,15]. Improved surface roughness of the composite diamond would facilitate metallization and brazing processes of the window and lower reflection loss of THz waves in principle.

3.2. Termination of MCD seams by UNCD growth

In contrast to nanometer sized-grains of UNCD, resulting from a fast secondary nucleation process, it is known that the grains of MCD exhibit a much larger size ranging from a few μm to tens of μm with irregular shapes. Therefore, voids, gaps and seams, are likely to form within the MCD columnar structure. The cross-section image of Fig. 6 clearly shows two seams in the MCD region. Fortunately, they are quickly terminated by growing UNCD over-layer on top. This is believed to attribute to the lateral growth mechanism of UNCD, as verified from Fig. 4(b) where UNCDs are seen to grow from a vertical wall. Though there are so far few reports concerning the lateral growth of UNCD, the process of diamond growth from sidewalls was reported and utilized to grow single crystalline diamond over-layers on micro-needle