L-3-1(Invited)
Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1257-1258

Progress in technologies of fabrication of single-crystal diamond wafers with inch-size area

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1. Introduction

Several outstanding material constants of single-crystalline diamond (SCD), e.g. hardness, refractive index, transparency, and so on, are the main reasons why this material is famous for the king of gem stones. It is well known that natural diamond has been utilized for mechanical tools as well. Since finding of a method of its artificial synthesis under high –pressure and –temperature circumstance [1], artificial ones have taken the place of the natural ones. Nowadays, production of artificial diamond for this purpose is much higher than that of natural ones [2]. In addition to such mechanical applications, several other possible applications, such as electron emitter devices [3], and X-ray window [4] have been studied.

Furthermore, SCD is also known to be one of the promising candidate materials to realize future high performance electronic devices such as Silicon (Si) and Silicon-carbide (SiC) owing to its excellent material constants as a wide-band-gap material [5, 6]. Its potentials such as stable performance in high temperature and rapid response have been performed partially [7, 8]. One of the big problems to realize its industrial use as a semiconductor material is difficulty to establish techniques to fabricate large sized wafer. Sizes of commercially available wafers of Si and SiC are 12 and 6 inches in diameters, respectively. On the other hand, unfortunately, commercially available size of SCD *pieces* is less than 10mm; typically, substrates with 2-3mm of edge length are used. Because, different from Si and SiC, growth area of SCD usually shrinks during the growth [9], it is not easy to enlarge the size of the seed crystal. One may be able to enlarge deposition area by controlling growth conditions very strictly [10, 11]. However, under such conditions, growth rate is typically quite low and requires impractically long time period of the growth to obtain a inch size crystal.

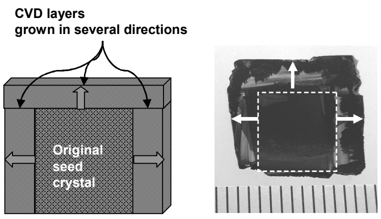

Fig. 1 (a) 3-dimensional growth of the bulk SCD (schematic), and (b) actual SCD substrate

Therefore, Mokuno, et al., conducted repetitive growth onto several (100) surfaces, and succeeded in fabricating the half-inch size SCD substrate form a seed with less than 10mm in edge length [Ref. 12 and Fig. 1] by using chemical vapor deposition (CVD). In addition, by using a lift-off process with high energy ion implantation, they also succeeded in fabricating freestanding substrates from the half-inch size substrate [Ref. 12 and Fig. 2].

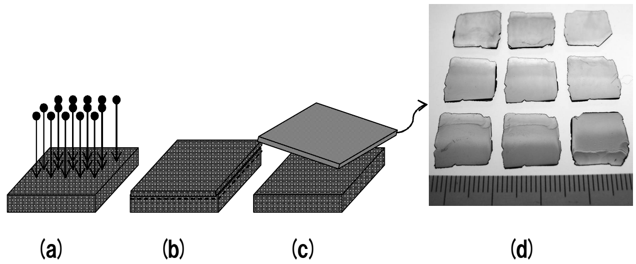

Fig. 2 Lift-off process with ion implantation (a) High energy ions are injected into a top surface of the substrate, and graphitic layer is generated beneath this surface (b) SCD layer is grown onto the same surface, (c) the graphitic layer is selectively etched. (d) Actual freestanding substrates with half-inch size.

2. Toward inch size wafer

In addition to the 3-dimensional growth, we have started to study a way to enlarge the wafer size more efficiently, that is, the mosaic wafer [Ref. 13 and Figs. 3(a), (b)]. A mosaic wafer is made by connecting relatively small size substrates into large size one. Then, one may remove the original constituent substrates by, for example, polishing [Fig. 3(c)]. To the best of author's knowledge, the maximum size of the mosaic wafer which was reported before our trial is 16×16 mm^2 of area which consists of 16 pieces of SCD plates with 4×4 mm^2 of area [10]. One of the most important controllable parameters is considered to be the alignment of the miss-orientation angles among the constituent substrates. Principally, it is possible to align the angles and directions of miss-orientation angles among the constituent substrates by cutting and polishing, preceding to the connecting. However, such processing are practically quite hard owing to its hardness.

The feature of our approach is the use of the freestanding substrates which were made from one identical seed substrate. Here, we shall call such substrates "clone" substrates. These clone substrates have the same characteristics with those of the seed substrate, and therefore these are the same with each other; all of substrates of Fig. 3(a) are clone substrates in this work. We found that the use of such clone substrates is very effective on fabrication of the mosaic wafers [14]. In the case of the "non-clone" substrates, the boundaries among the substrates are not smooth even if the difference in the angles is less than 1 degree. On the other hand, in the case with the clone substrates, the boundaries are smoothly covered, and constituent substrates are connected stiffly. Furthermore, we found that the lift-off process with ion implantation can be applied on such mosaic wafers [Refs 14 and 15, and Figs. 3 (d)-(e)] as well.

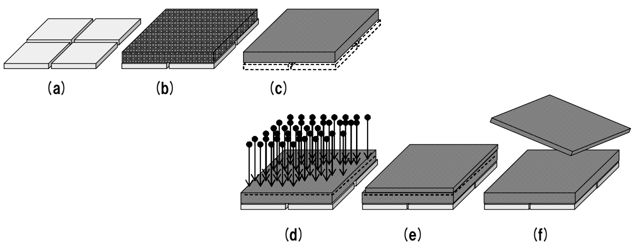

Fig. 3 Process to make mosaic wafers (a) arrange constituent substrates, (b) SCD layer is grown on them, and these substrates are connected into one wafer, and (c) the constituent substrates are removed. In our approach, the liftoff process is applied on the mosaic wafer (b) as shown in Figs. (d)-(e) similar to that with Fig.2.

In figure 4, actual freestanding mosaic wafers are shown with the constituent clone substrates. Clone substrates with approximately $10\times10mm^2$ of area are cut out of the freestanding clone substrates with half inch size as shown in Fig. 4 (a). Clone mosaic wafers with approximately $20\times 20mm^2$ of area, which originates from four constituent SCD pieces, are shown in Fig. 4 (b). One may notice that the boundaries are almost invisible. Then, two of them are connected into one wafer with approximately $20\times40mm^2$ of area as shown in Fig. 4 (c).

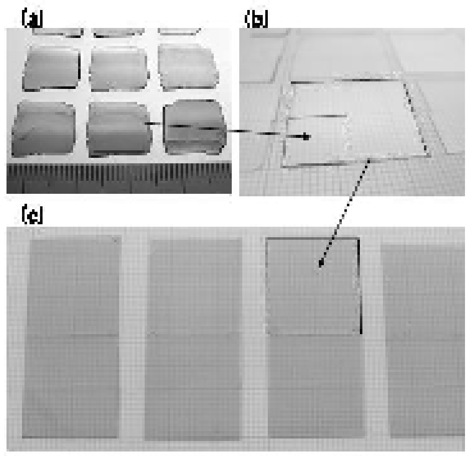

Fig. 4 (a) Original half inch size SCD substrates. Rectangular substrates are cut out of these substrates. (b) Mosaic wafers with four constituent SCD clones. (c) Mosaic wafers with eight constituent SCD clones. Intervals of the scale in (a) and quadrille lines in (b), (c) represent 1mm.

In this way, the wafer size can be easily enlarged in comparison with the conventional ways. Now we are going to enlarge the wafer size into 2-inch size.

3. Summary

We have developed the process to enlarge the seed SCD and lift-off the freestanding wafers. Mosaic wafers by using the clone substrates enabled us to enlarge the wafer size very efficiently. Now, we are going to enlarge the wafer size into 2-inch size. For realization of this, it is important to control growth condition, for example, to reduce non uniformity of the growth rate and internal stress inside the wafers. In addition, quality of the original seed crystal is important for that of the resultant wafers. Furthermore, developments of processing technique to treat such inch-sized SCD wafers are left for future work.

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