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Diamond Electronics: Past Perspectives and Future Prospects

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Abstract

Diamond is so called "the ultimate semiconductor" in the past 30 years, because of its superior material properties such as high avalanche breakdown field, high carrier mobility/velocity, low dielectric constant, chemical inertness and radiation hardness. These advantages of diamond are originated from the strong covalent bonds of carbons. Recently, diamond devices with high blocking voltage/high current capability at high temperature or X-ray radiation hardness have been reported.

1. Introduction

The strong covalent bonds of carbons in crystal diamond give wide variety of superior material properties such as wide bandgap, high avalanche breakdown field, highest thermal conductivity in the materials, high carrier mobility and saturation velocity. Thanks to the properties, diamond is one of the most promising material for high-power/low-loss/high frequency and high temperature devices [1]. Recent progress of epitaxial growth with doping control enables electron devices with high blocking voltages [2].

The current status and future prospects of diamond electron device researches including wafer technology, device processing and performances will be discussed in this paper.

2. Wafer technology

For the production of single crystal diamond wafer, especially for electron devices applications, microwave plasma assisted chemical vapor deposition (MWCVD) is used because of its high controllability of doping concentration and crystal quality. At present, Japan and Europe lead the technologies to enlarge the wafer size as well as the improvement on the crystal quality. Smart-cut technique which doesn't need the wafer slicing is one of the promising way to realize low-cost and high quality wafers [3]. Utilizing this technique, large scale >2'' single crystal mosaic wafer is available [4].

Spin-off companies in Japan started their shipments of single crystal and heteroepitaxial wafers. The typical density of dislocations in the single crystal and the heteroepitaxial wafers are 10^{2}-10^{5} and 10^{6}-10^{9} /cm^{2}. The progress of wafer size diameter on the single crystal and the heteroepitaxial diamond are summarized in figure 1. The growth cost of the diamond wafer including polishing and cutting process will be decreased according to the expansion of the market of lab-grown single crystal diamond gemstone which is expected to be 4B$/year in 2030.

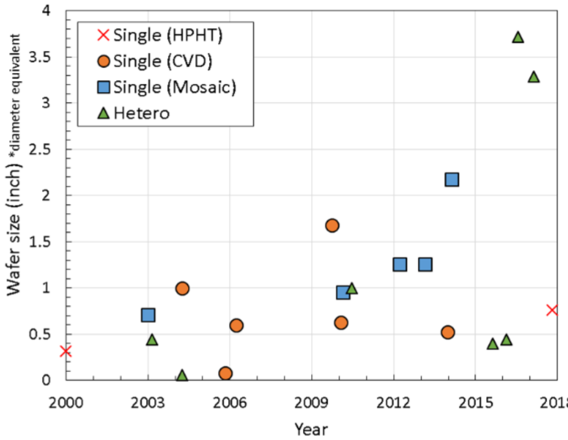

Fig. 1 Progress of the wafer size of single crystal and heteroepitaxial diamond

3. High power device under high temperature condition

Up to now, high voltage > 3 kV or high current density > 3kA/cm^{2} Schottky barrier diodes (SBDs) have been reported [5-8]. The figure of merit of power devices calculated by the breakdown voltage V_{BD} and the specific on-resistance $R_{on}S$ as $V_{BD}^{2}/R_{on}S$ reaches 244 MW/cm^{2} on a pseudo-vertical diamond SBD without edge-termination structure [9]. This value is close to the SiC's unipolar limit and the maximum of diamond devices operated at room temperature. According to the deep activation energy of acceptor boron in diamond, the carriers are not activated at room temperature and the resistivity goes to minimum between 200 to 300 °C. The one order of magnitude of reduction in conduction loss compared to SiC devices is available at this temperature range, since it's comparable at room temperature [2]. The long-term stability of metal-diamond interface under high temperature conditions > 400°C have been confirmed. The specific Ohmic contact resistivity of Ti on p+ diamond is less than 10^{-6} Ω-cm^{2} after 400hr at 800°C [10]. Ru or Pt Schottky contact works after 1500hr at 400°C without degradation of the ideality factor or the barrier height [11]. The breakdown field of SBDs estimated from the thickness and the doping concentration of the drift layer are less than 4 MV/cm, which is less than that half of the avalanche breakdown field of diamond. Electron beam induced current (EBIC) map of SBDs under the reverse biased condition reveals that the field enhancement occurs at the edge of the electrode and the existence of hot spots which initiates breakdown [12]. The edge-termination structure and appropriate fabrication technique are highly required to improve the breakdown characteristics of diamond devices.

For the switching devices, unipolar transistors such as metal-semiconductor field-effect transistors (MESFETs) [13], junction FETs (JFETs) [14] and metal-oxide-semiconductor FETs (MOSFETs) have been reported. The breakdown voltage of the MESFET increases with increasing gate to drain distance L_{GD} and reaches more than 1.5 kV when L_{GD} is 30 µm. The typical current density characteristics of diamond MESFET are shown in figures 2.

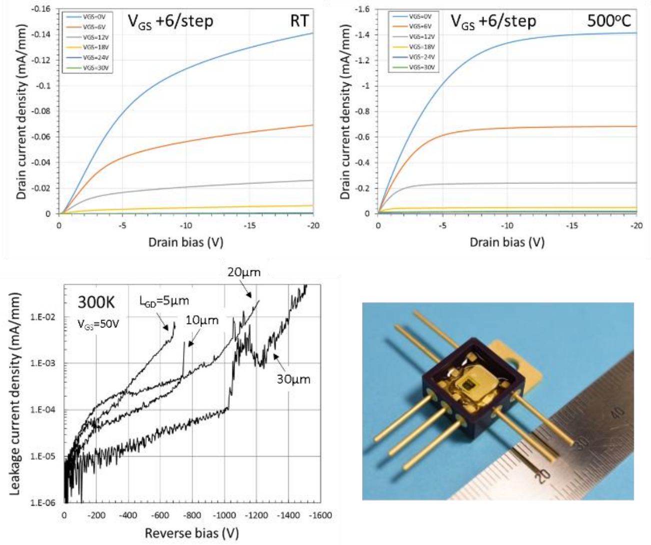

Fig. 2 Typical current voltage characteristics of diamond MESFET. Static characteristics at room temperature and 500°C are shown. The breakdown voltage increases with increase of L_{GD}.

4. Radiation hard & high temperature devices

Important applications of semiconductor diamond are the power converters and the integrated circuits in the nuclear plant or in the aerospace vehicles, where the high energy particles irradiated. High radiation hardness of semiconductor diamond is one of the advantage for this applications. The statistic characteristics of the diamond MESFET before and after the X-ray irradiation is shown in fig. 3.

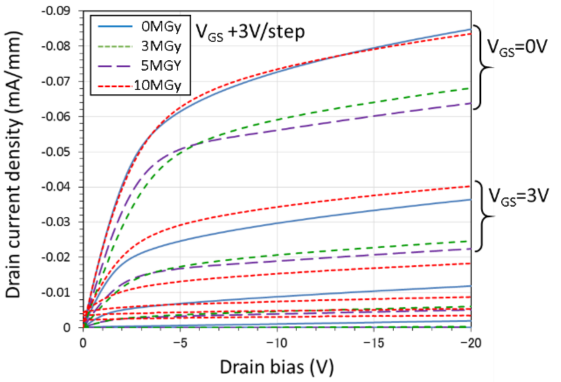

Fig. 3 Current voltage characteristics of diamond MESFET before and after X-ray irradiation.

The increase of the surface leakage current between Schottky gate and Ohmic drain/source was confirmed after the X-ray irradiation, accordingly the on/off ratio was degraded from 4 to 2 orders of magnitude. However, the maximum drain current and transconductance were almost constant to the irradiation, which indicates the high radiation hardness of diamond devices on X-ray.

5. Conclusions

The wafer size of single crystal diamond are extended and will reach to 4 inches in a couple of years. The growth cost is expected to decrease according to the growing of the single crystal diamond market. Researches on diamond semiconductor devices are progressed, however, the breakdown voltage is much lower than that expected from the material properties. Optimized edge-termination structure and appropriate device fabrication processes are highly required to improve the performances.

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