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Floating Field Rings for Pseudo-Vertical Diamond Schottky Barrier Diodes

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Abstract

Surface electric field distribution of non-terminated and terminated architecture Schottky electrode under reverse bias was analyzed by electron beam induced current (EBIC) technique. A decrease of the EBIC signal was clearly observed at the edge of a terminated Schottky barrier diode (SBD) as compared to a non-terminated one. The best spacing given the best electric field distribution was confirmed by 2D TCAD simulations analyses. An influence of ring spacing on leakage current triggering was noticed.

Introduction

Among the wide bandgap semiconductors, diamond with its exceptional physical and electrical properties such as a wide bandgap energy (5.5 eV), high breakdown field (>10 MV/cm), high thermal conductivity (22 W/cm.K) and high hole mobility (2000 cm^2/V.s), is one of the most suitable materials for high power and high temperature electronics applications. Promising results on diamond Schottky Barrier Diodes (SBDs) have already been reported in the literature [1–3]. However, the breakdown in diamond Schottky devices is still an issue and remains low compared to the diamond material capabilities [4]. One of the issues that limit the device operation in reverse state is the electric field crowding at the edge of the main contact causing a premature breakdown. The estimated electric field peak at the edge is about three times higher than the one at the center of the electrode [5]. This crowding phenomenon at the edge can be relaxed by using a special surface architecture called edge termination providing a uniform distribution of the electric field. In this study, we analyze a fabricated floating field ring SBD and compare it with a 2D simulated structure. The effectiveness of the edge termination integration was pointed out using electron beam induced current (EBIC) technique to map the surface electric field distribution.

Experimental

Diamond SBDs with and without floating field rings (FFR) were fabricated. Starting from a high-pressure high-temperature (HPHT) diamond single crystal, a heavily boron doped (p+) layer followed by a lightly boron doped (p-) layer were epitaxially grown by chemical vapor deposition (CVD). The boron concentration of the p+ layer is $>2\times10^{20}$ cm^{-3} for a thickness of 1 μm. The boron doping level and the thickness for the p- layer are 1×10^{16} cm^{-3} and 0.95 μm, respectively. The p- layer was then etched in the corner of the sample in order to have access to the p+ layer. Ti(30 nm)/Pt(30 nm)/Au(100 nm) Ohmic metal contact was then deposited on the etched places and annealed at 450 °C under vacuum. Finally, molybdenum Schottky metal was deposited by e-beam evaporation using the lift-off technique. EBIC analyses to observe the distribution of the electric field and electrical characterization were performed on the devices. All measurements were done under vacuum and at room temperature. More details on the experimental approach can be found in [6].

Results and discussion

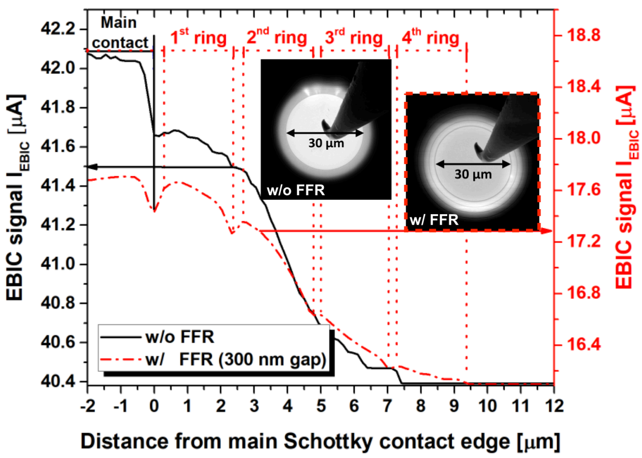

Fig. 1. EBIC signal as a function of distance from main Schottky contact edge for SBD w/o FFR and w/ FFR. The gap between the rings is 300 nm. The collected EBIC signal is more than two times higher w/o FFR than w/ FFR.

EBIC signals as a function of the distance from the main Schottky contact edge for both non-terminated (w/o FFR) and terminated SBD (w/ FFR and 300 nm gap between rings) are shown in Fig. 1. The corresponding EBIC images are also shown. Measurements were done under a reverse bias of 120 V for both devices. At this reverse bias, leakage current densities of SBD w/o and w/ FFR – 300 nm gap were 10^{-9} A.cm^{-2} and 10^{-5} A.cm^{-2}, respectively. Even if the leakage current was higher w/ than w/o FFR, EBIC signal was low due to a better electric field distribution. The bright regions correspond to the presence of the electric field at the surface and the dark regions to the absence of the electric field. SBDs w/o and w/ FFR have different EBIC signal (left and right y-axis, respectively). The one for SBD w/o FFR is more than two times higher than the one w/ FFR. As EBIC signal is a consequence of electric field presence and strength, then the maximum electric field of the SBD w/o FFR is higher than the maximum electric field of the SBD w/ FFR. This figure shows the effectiveness of using FFR as edge termination for SBDs.

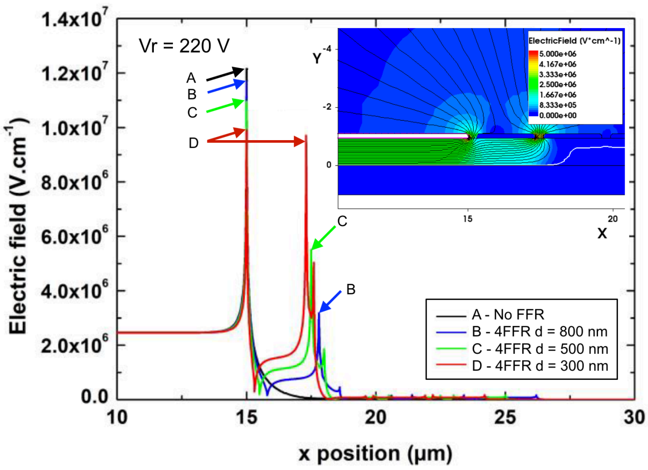

Fig. 2. Electric field distribution at metal/diamond interface (diamond surface) for SBDs with 800 nm, 500 nm, 300 nm and no gap. Best result obtained for d = 300 nm.

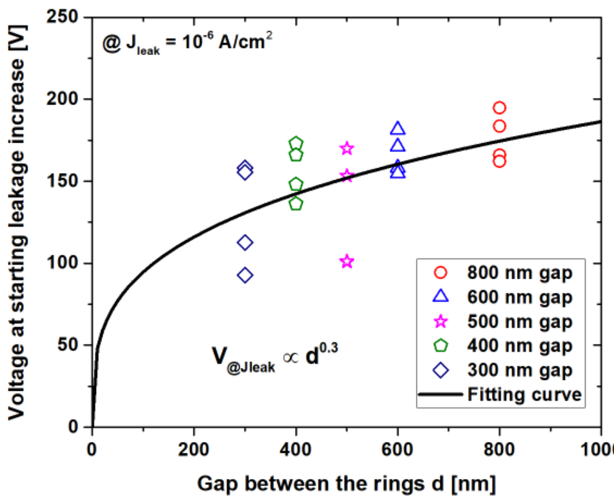

Fig. 3. Dependence of the gap between the rings on leakage current start. Arcing phenomena is one of the responsible for leakage current increase.

2D TCAD simulations using Synopsys Sentaurus were performed to confirm the best ring-to-ring spacing previously determined by EBIC analysis. The simulated devices have the same parameters as the fabricated ones. Figure 2 shows the simulated surface electric field distribution for FFR with 800 nm, 500 nm and 300 nm gap between the rings and w/o FFR under an applied reverse bias voltage of 220 V. Among these different gaps, SBD w/ 300 nm gap for FFR exhibits the lowest electric field peak. Results obtained by simulation and results obtained by EBIC analysis are in good agreement. However, maximum breakdown voltage obtained experimentally (>250 V) is still far from the 1D breakdown voltage of the device (830 V). The presence of hotspots, arcing, and non-uniform interface may limit the off-state capabilities [6,7]. A further optimization is needed, such as gradient increase of ring-to-ring distance and rings width, and surface passivation by oxide.

It has also been noticed that there is a dependence of the leakage current start with the gap between the rings. At a fixed leakage current density level, when the gap reduces, the voltage at which the leakage current density starts drastically decreases. By summarizing the obtained data for different gaps, a tendency appeared. The voltage at which leakage current starts is proportional to the gap between the rings as $V@_{Jleak} \propto d^{0.3}$. SBDs w/o FFR were not considered. This early triggering of the leakage current could be associated to arcing phenomena that occur at high bias.

Conclusion

The introduction of FFR as edge termination demonstrated effectiveness in distributing the electric field at the surface of the device, as observed with EBIC technique. TCAD simulation study confirmed the experimentally obtained results. Despite the obtained 2.6 MV/cm, device capabilities are still limited compared to the expected one due to arcing effect for narrower gaps, and a lake in optimization design before fabrication. A new approach with optimized design and fabrication will be presented. Edge termination investigation is an important step for device performance and breakdown parameter extraction.

Acknowledgements

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