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Dynamic Properties of Diamond High Voltage PIN Diode

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Abstract

Basic investigation of a diamond pin diode dynamic properties has been done using a clamped inductive switching. When the diamond pin diode was switch-off, the reverse recovery occurred. According to the switching conductions, the reverse recovery in diamond pin diode may lead to a huge reverse current flow. Such a phenomenon was ascribed to the well-known reverse recovery failure, namely, the dynamic avalanche breakdown. Thus, the rectification properties of the diamond pin diode was lost at a relatively low reverse blocking voltage compared to the static mode value.

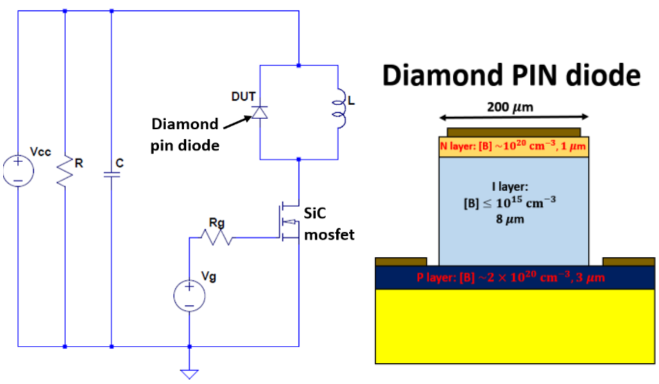
1. Introduction

According to its outstanding electrical and thermal properties, diamond is one the best semiconductors for the high temperature, high blocking voltage, and fast switching devices. The feasibility of diamond devices was highly demonstrated thanks to elementary devices reported (SBD, pin diode, MESFET, JFET, Hydrogenated-diamond FET). Moreover, the successful achievement of the electronic grade silicon-based heteroepitaxially grown diamond substrates [1], opens the door towards the diamond devices fabrication at the industrial scale. Among the diamond devices, the pin diode is one of the most advanced and promising, both by its forward characteristics and by its reverse blocking characteristics [2, 3]. Recently, a diamond pin diode with a critical field of 4.3 MV/cm (higher than the theoretical limit of the SiC material) was reported [4]. Besides their electrical performances in static, the reliability of the pin diodes is in major part defined by their dynamic features. In switching applications, the pin diode is commutated from a conduction state to blocking state (switch-off), and inversely (switch-on). During the switch-off process, the extraction and the exhaustion of the stored charge in the pin diode base region (conductivity modulation), may induce several reverse recovery failures such as the snappy recovery or the dynamic avalanche breakdown.

In this work, the dynamic properties of a diamond pin diode was investigated. This study was focused on the switch-off of the diamond pin diode in order to highlight the main failures occurring during the reverse recovery.

2. Contents

The switch-off characteristics of a diamond pin diode was investigated using a standard clamped inductive switching system as shown on the Figure 1.a). Diamond pin diode was used as the free-wheeling diode. A ferrite toroidal inductor with an inductance of 1619 µH was used. The main switch was a SiC power mosfet CMF20120D. This mosfet was driven using an EVIC420 driver, and a 10 Ω gate resistance.



a) b)

Figure 1: a) clamped inductive switching circuit, b) diamond pin diode structure

Figure 1 b) shows the structure of the diamond pin diode. A pseudo vertical n^+ip^+ diamond pin diode was used. A stack comprising a heavily phosphorus-doped diamond layer (n^+-layer), an undoped diamond layer (i -layer), and a heavily boron doped layer (p^+-layer) were grown by Microwave Plasma enhanced Chemical Vapor Deposition (MPCVD) on a Ib HPHT diamond substrate (p-layer). The n^+ layer was 0.5µm thick with an average phosphorus concentration [P] ~ 10^{18} cm^{-3} (this value was determined by secondary ion mass spectroscopy SIMS). The impurities concentration (boron and phosphorus) estimated by SIMS in the i-layer (8 µm thick) were below the detection limit (P), [B] < 10^{15} cm^{-3}). The average SIMS boron concentration in the p^{+}layer (3 µm thick) was about 10^{20} cm^{-3}. An ICP etching was performed to delineate the pseudo-vertical pin diodes (200 µm diameter diodes). Metallic contacts (Ti/Pt/Au stack) were then deposited on the n^{+}layer and the p^{+}layer in order to fabricate the cathode and anode contacts, respectively (confer Fig. 1 b)).

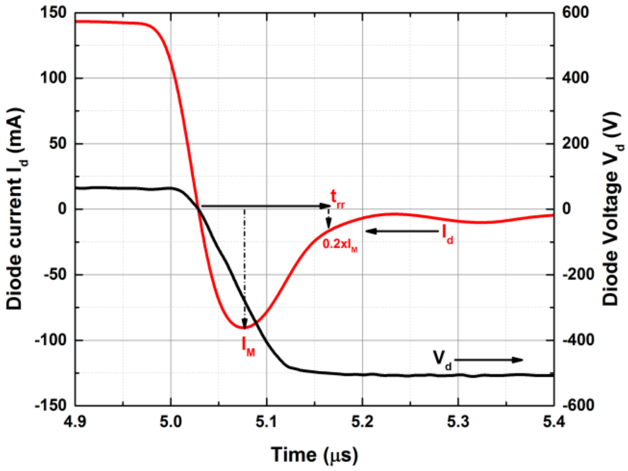


Figure 2: Reverse-recovery waveforms of the diamond pin diode

Figure 2 shows the typical switching-off characteristics of the fabricated diamond pin diodes. The diode was first switch-on. A steady state forward current of 144 mA (@150 $A \cdot cm^{2}$) was reached, and the forward voltage drop was about 66 V. The diamond pin diode was then switch-off. A reverse recovery occurred before the diamond pin diode reverse blocking state at -500 V. A 137 ns reverse recovery time t_{rr} was measured. The reverse current peak value I_{RRM} was about 90 mA (71 $A \cdot cm^{2}$) and the reverse recovery charge was 8 nC.

Figure 3 shows the current and the voltage waveforms when the diamond pin diode was switched the conduction state to a reverse blocking state at -600 V. The diamond pin diode lost its blocking features so that a huge reverse current flow occurred. The voltage build-up speed across the diamond diode was 6×10^{3} V/µs, and the switching rate was 140 A/µs. The diamond current started to be negative when the reverse voltage drop was about -300 V. The diode current then increased with a rate of 140 A/µs. At -2 A (@ 430 V), the reverse voltage started to decrease, and tended to stabilize around -300 V. On the other hand, the reverse current still increased and seemed to level off at around -12.5 A.

This phenomenon was ascribed to the dynamic avalanche breakdown. Indeed, the free carrier (electron in the case of diamond) flows through the pin diode space-charge region during the switch-off process. The free carrier density adds to the background doping to an effective doping level

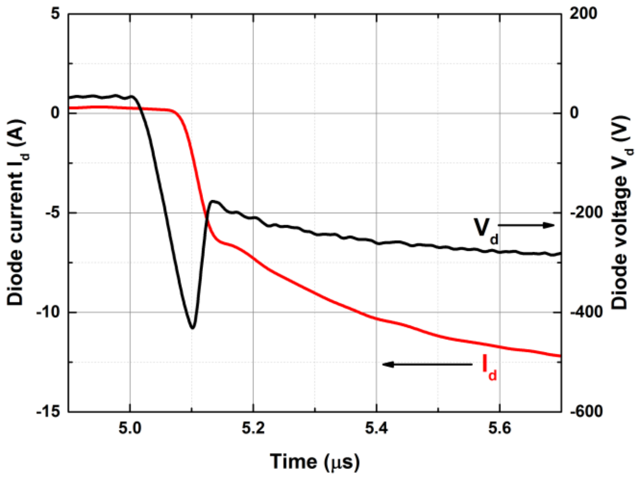


Figure 3: dynamic breakdown of the diamond pin diode

[5]. Thus, the maximum electric filed at the junction ($n^{+}i$ interface) increases. The dynamic breakdown occurred if the maximum electric reached the avalanche field due to this mechanism [5]. In the case of the diamond pin diode investigated, an electric field value of 6×10^{5} V/cm was expected for a 600 V reverse blocking voltage under the punch-trough assumption, and in static. This field value was far below the critical field value of diamond (10 MV/cm). Therefore, the mechanism inducing the dynamic avalanche breakdown seemed not enough to explain the data reported on the Figure 3. However, the basic device structure used in this study (without any junction extensions), should suffer from the electric field crowding, thus leading to a much higher field value at the device corners.

In order to explain such experimental data, a computer simulation (TCAD simulation) has been performed. The charge carrier dynamic during the reverse recovery of the diamond pin diode will be discussed. The electric field distribution in static, and during the reverse recovery will be introduced. The influence of the free carrier flow on the electric field distribution will be discussed. The conditions needed to observe the dynamic breakdown of a diamond pin diode will be investigated.

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