# DEVELOPMENT OF 100 NS WIDE BLUMLEIN TRANSMISSION LINE PULSE GENERATOR FOR: STUDY OF HIGH ELECTRIC FIELD PROPERTIES IN BORON-DOPED DIAMOND

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## Abstract

Diamond can become highly conductive due to impurity impact ionization and avalanche effects when sufficiently doped with boron and exposed to high electric field. Knowledge of those effects is important for the fabrication of potential novel high power electronic devices. High currents and voltages make characterization of impurity impact ionization uneasy and require pulsed characterization measurement methods to limit thermal effects. In this work, we first present the synthesis of epitaxial boron doped diamond layers by Plasma Enhanced Chemical Vapour Deposition and their microfabrication process and then we study their electrical properties in high electric field. Second, we describe the home-made Transmission Line Pulse current-voltage (I-V) characterization setup based on a Blumlein pulse generator. Finally, quasi-static I-V characteristic has been measured showing impurity impact ionization and avalanche effect at high electric field.

**Keywords:** Impact ionization, Transmission Line Pulse generator, boron doped diamond, micro-technology

## 1. INTRODUCTION

Low boron doped diamond is a usually highly resistive material and behave as a semiconductor because of the high boron acceptor ionization energy. Nonetheless it becomes highly conductive when exposed to a high electric field due to impurity impact ionization and avalanche effects [1, 2]. Knowledge of these effects in diamond is important for the fabrication of potential novel high power devices. Measurement of carrier multiplication and the avalanche threshold field requires an electrical characterization method that can work with high voltage and high current and is also sufficiently fast to minimize thermal effect. In this paper, we describe 1. the fabrication process of epitaxial boron doped diamond layers, 2. the micro-fabrication process of high electric field test devices, 3. the homemade 100 ns Blumlein Transmission Line Pulse (TLP) generator and finally we present the measured electrical properties of boron doped diamond measured using our newly developed TLP generator. This article is divided in 4 different main sections: 1. Introduction, 2. Epitaxial boron doped diamond growth, 3. Microfabrication processes, 4. Electrical characterization which includes the Blumlein transmission line pulse generator development and experimental results and 5. Conclusion.

## 2. EPITAXIAL BORON DOPED DIAMOND GROWTH

Epitaxial boron doped diamond layers were grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) using a commercial ASTeX 5010 reactor. Prior to deposition, (100) oriented 3×3 mm$^2$ substrates were cleaned in a hot oxidizing mixture of $H_2SO_4$ and $KNO_3$ for 10 min. The substrates were then thoroughly washed in DI-water. Immediately before loading in the PECVD reactor, the sample were ultrasonically cleaned in acetone and alcohol and dried with clean dry air. Diamond growth was divided into four different steps whose conditions are reported in **Table 1**:

- The 1st step of a pure hydrogen plasma is twofold: 1. to rise the substrate temperature towards the one used during the growth step and 2. to clean the diamond substrate thanks to the high temperature and the energetic atomic hydrogen present in the plasma
- The 2nd step aims to remove the near surface structural defects by dry chemical etching using an oxygen diluted in hydrogen plasma
- The 3rd step is carried out using growth conditions without carbon and boron precursors. This step aims to set the substrate temperature close to the one used during growth and to purge the reactor from oxygen species from the etching step before diamond growth
- The diamond growth (4th step) starts with the addition of carbon (methane) and a boron precursor (trimethylborane). In this work, epitaxial layers were grown with various boron to carbon ratios of: 20, 40, 60, and 549 ppm.

**Table 1** Description of diamond growth process conditions

| Step | Process gas composition | Pressure (mbar) | MW power (W) | Time (min) |
|---|---|---|---|---|
| 1 | $H_2$ | 100 | 500 | 10 |
| 2 | $O_2$ (1 %) - $H_2$ (99 %) | 100 | 700 | 10 |
| 3 | $H_2$ | 100 | 700 | 10 |
| 4 | $H_2$ (∼99 %) - $CH_4$ (∼1 %) - $B(CH_3)_3$ (variable) | 100 | 700 | 30 |

## 3. MICROFABRICATION PROCESSES

Microfabrication technologies have been developed in parallel with silicon microelectronics for several decades. Chemical vapour deposition (CVD), physical vapour deposition (PVD), photolithography, etc. are the basic processing techniques. Nowadays technologies allow the processing of wafers as large as 300 mm, with alignment accuracy 0.5 µm [www.suss.com/en/products-solutions/mask-aligner/ma300-gen2] or the fabrication of sub-micrometre size transistors. However, standard mono-crystalline diamond substrate size is well below 1 cm, making the initially simple step of photoresist coating more complex as the so-called edge bead is of the same size as the substrate. To tackle this issue, we developed a specific processing method based on an epoxy mould. Once the photoresist was homogeneously coated without edge bead, test devices have been fabricated using standard microfabrication processes.

### 3.1. Epoxy mould fabrication process

The purpose of the epoxy mould is simple: it is to minimize the step and/or gap at the edge of the diamond substrate to ease photoresist flow during the spin coating step and move the edge bead formation away from the diamond substrate. This method relies on reproducible substrate dimensions, flexibility and chemical stability of the epoxy mould. Moulds are fabricated using 3M™ Scotch-Weld™ Epoxy Adhesive 2216 B/A grey in a multi-step process (see **Figure 1**) described as follows. The glue's two different components are weighted on a precision scale according to the prescribed weight ratio. The two components are mixed to obtain a uniform mixture. The mixture is placed in vacuum to outgas in order to remove any bubbles. The prepared epoxy glue is then spread on a piece of Parafilm "M". A standard sized diamond substrate is dropped onto the glue and covered by a second piece of Parafilm "M" whilst being careful not to trap air bubbles in the glue at and near the diamond sample. This sandwich structure is then pressed between two microscope glass slides until the full removal of epoxy glue at the interface between the diamond sample and the two Parafilm "M" pieces. Complete removal of epoxy glue is easily checked as it is then possible to see through the whole layer structure at the diamond position (see **Figure 1b**). The glue is left to cure at room temperature for 24 hours under a small weight (see **Figure 1c**). The glue is easily separated from the Parafilm “M” due to its poor adhesion on this surface. The resulting epoxy piece has a hole of the exact dimensions of the diamond substrates used for growth of epitaxial layers (see **Figure 1d**). Samples with epitaxial layers can then be mounted on this mould such there are no visible gaps or steps between the sample and the mould surfaces. The mould with the diamond substrate is then attached, for instance, to a 2 inch silicon wafer (see **Figure 1e**), to spin-coat the photoresist without edge bead formation on the sample. The diamond sample is then gently removed from the epoxy mould to be further processed.

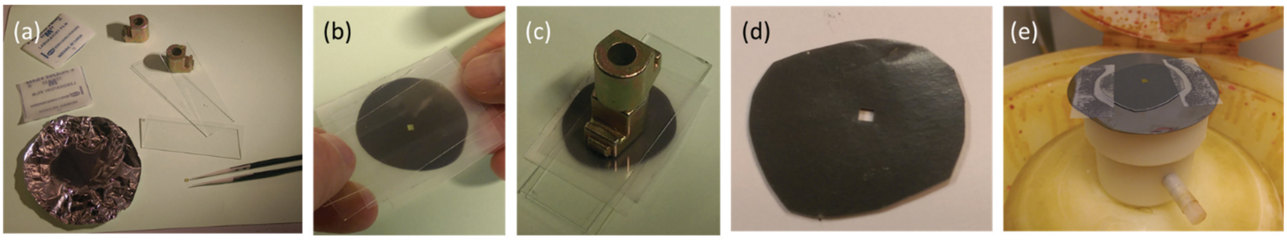

**Figure 1** Epoxy mould fabrication steps: (a) Mixed and outgassed 3M™ Scotch-Weld™ Epoxy Adhesive 2216 B/A, Parafilm “M”, microscope glass slides, small weights, tweezer and diamond substrate, (b) Pressed glass slides, Parafilm “M” parts, epoxy and diamond sandwich, (c) Epoxy mould left to cure under a small weight, (d) Dry mould, (e) diamond sample mounted on the epoxy mould ready to be spin coated

### 3.2. Test device fabrication

Samples with epitaxial boron doped diamond layers were first cleaned in a hot oxidizing mixture of $H_2SO_4$ and $KNO_3$ for 10 min. Samples were then thoroughly washed in DI-water and finally ultrasonically cleaned in acetone and alcohol and dried with clean dry air. The epitaxial boron doped diamond layer was then coated with layers of Ti (10 nm) and Au (90 nm) by vacuum evaporation. Circular TLM structures with electrodes with an inner ∅ of 150 μm and various inter-electrode gaps (5 to 40 μm) were patterned by photolithography and etching techniques. A 1 µm thick positive photoresist (ma-P 1200 from Micro Resist Technology) was deposited by spin-coating as described above at a rotation speed of 3000 rpm for 30 seconds and baked on a hot plate at 110°C for 2 minutes. The electrodes were patterned using maskless lithography. The resin was exposed using a microwriter with a 405 nm laser. Exposed samples were developed in “mr-D 526/S” developer for c.a. 30 seconds. Finally, the electrodes were obtained by wet chemical etching using $KI/I_2$ Au etchant and diluted HF (0.1%) to etch Ti. The photoresist is simply removed in acetone.

## 4. ELECTRICAL CHARACTERIZATION

### 4.1. Transmission Line Pulse (TLP) measurement setup and generator

The schematic of the TLP measurement setup developed at the Institute of Physics, Prague, to measure quasi static I-V characteristics is represented on **Figure 2**. The setup is computer automated using a specifically developed Labview program to generate pulses, to collect the current and voltage waveforms and to display and save collected data. This setup is based on Blumlein pulse generator charged by a SM400-AR-8 DC power supply from Delta Electronics which can deliver voltages up to 400 V. The output voltage is computer controlled via the power supply’s (0 - 5 V) analogue control input through an USB-6009 data acquisition (DAQ) device from National Instruments. The DAQ is also used to control the relay which triggers the pulse generator. The device under test (DUT) is connected to the generator through a 74CJ-APT-KS-100GP/50 Probe Holder with 100 μm pitch from American Probe via a micro-positioner DPP105-PTH from Cascade Microtech. The current and voltage waveforms are measured using a Tektronix TDS 2004C oscilloscope via a Tektronix CT1 current probe and a pick-off tee (20 dB voltage attenuation), respectively.

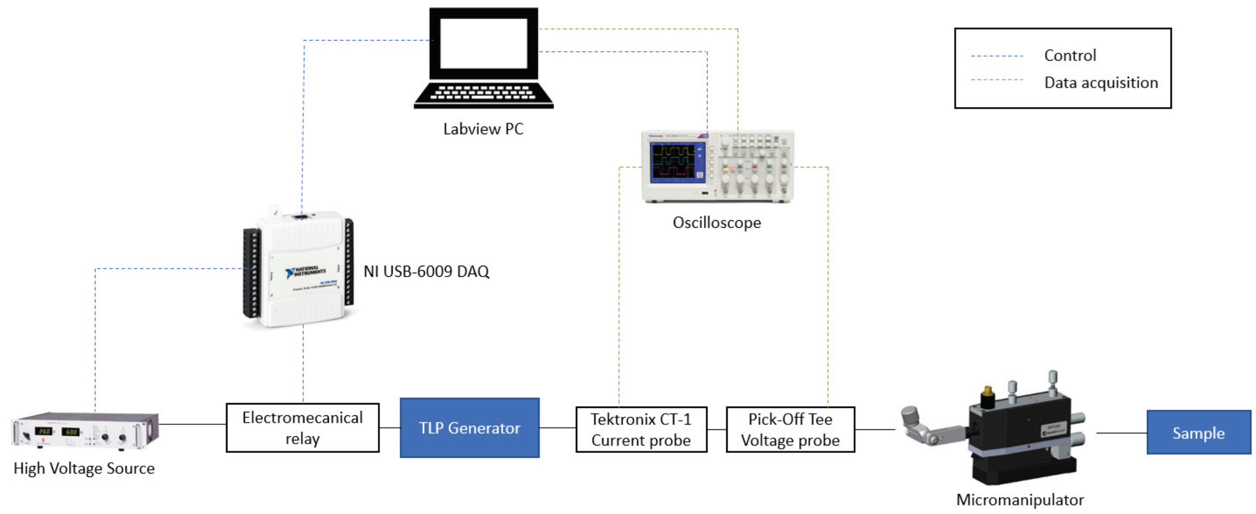

**Figure 2** Schematic of transmission line pulse measurement setup

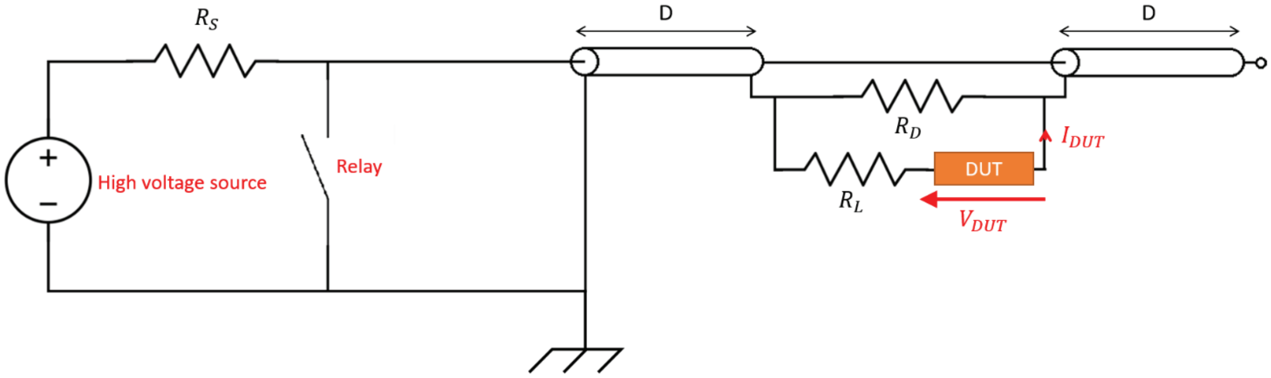

**Figure 3** Electrical scheme of the Blumlein generator

## 4.2. Blumlein pulse generator

The core part of the transmission line pulse measurement setup is the pulse generator. The TLP generator develop at the Institute of Physics, Prague is a Blumlein type generator. The main advantage of the Blumlein generator over conventional TLP generator is that it can generate higher voltage pulses [6]. The amplitude of the voltage pulse varies with the DUT impedance. The voltage pulse can reach twice the power supply voltage value at high DUT impedance at the expense of multiple refections. The amplitude of the voltage pulse is equal to the power supply voltage for 100 Ω impedance and further decreases at lower impedances. Our 100 ns pulse wide Blumlein generator consists of a 2D = 20 m long RG58C/U BNC cable with a metal mesh outer conductor disconnected at half its length. The DUT is inserted between the two insulated metal mesh parts of the BNC cable (see **Figure 3**). The BNC cable is charged through a high resistance ($R_s$ = 4.7 MW) compared to the characteristic impedance of the cable (50 Ω) with a time constant of $\tau \cong$ 10 ms. The 100 ns voltage pulse is triggered by shorting the inner and outer conductor of the cable using a SIL05-1A85-76D3K lead-free electrical relay from Standex-Meder Electronics which generates a wave front which propagates in the BNC line. The wave front undertakes several transmissions and reflections stages, which generate the high voltage pulse at the DUT end (see ref [7]). The actual Blumlein generator includes 1. a $R_D$ = 100 kΩ resistor in parallel with the DUT to avoid having a floating ground on the right-hand side of the BNC cable as it can be electrically isolated in case of too high DUT resistance and 2. a $R_L$ = 50 Ω (MP930 from Caddock) in series with the DUT whose role is to adapt the impedance of the Blumlein generator (100 Ω) to the BNC cable ($Z_0$ = 50 Ω) which is used to connect the DUT.

### 4.3. Experimental results

**Figure 4a** shows the pulse voltage and current waveforms generated with the TLP generator. The voltage step at t = 20 ns is due to the time delay induced by the BNC cable length between the sample and the voltage probe. At t = 45 ns, the voltage and the current suddenly decreases and increases, respectively, i.e. the sample becomes highly conductive. This behaviour is attributed to the combination of impurity impact ionization and avalanche effect above critical voltage and electric field threshold. By averaging the voltage and current values over plateau, one can plot the quasi-static current-voltage characteristic (I-V). The mean values were calculated between 80 and 100 ns. In these measurements, a 500 Ω resistance has been connected in series with the diamond test sample to safely limit the current. The quasi-static I-V characteristic is not linear (see **Figure 4b**). The resistance of the sample is decreasing with the voltage. When the critical electrical field voltage is reached, the resistance sharply drops, the voltage decreases and the current increases. Simultaneously, electroluminescence and current filamentation are observed.

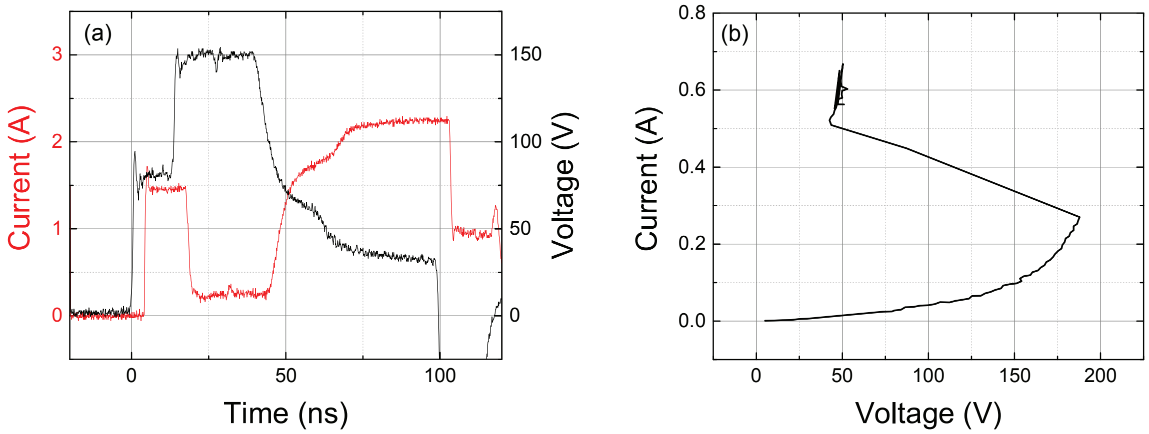

**Figure 4** (a) Pulsed voltage (black curve) and current (red curve) waveforms at critical electrical field/voltage and (b) Quasi-static I-V characteristic of an epitaxial boron doped diamond layer grown with B/C = 60 ppm and 5 µm gap between electrodes

## 5. CONCLUSION

In summary, we review the synthesis of epitaxial boron doped diamond layers and their microfabrication process to study diamond's electrical properties in high electric fields. For this purpose, we developed a transmission line pulse characterization setup based on a Blumlein generator. Blumlein generator advantageously generates high voltage pulses to study the avalanche effect in boron doped diamond, as the pulse amplitude is maximized for high resistive samples. Quasi-static I-V characteristic of fabricated devices measured using a newly developed setup exhibit 3 electrical conduction regimes: linear ohmic conduction at low voltage, super-linear increase due to impurity impact ionization at higher voltage and finally above the critical voltage threshold, the resistance sharply drops. Under these conditions, current filamentation and electroluminescence is observed.

## ACKNOWLEDGEMENTS

***The financial support from the following sources is gratefully acknowledged: The Czech Science Foundation grant ID: GACR 17-05259 S and J. E. Purkyne fellowship awarded to V. Mortet by***

***Academy of Sciences of the Czech Republic. The authors also acknowledge the assistance provided by the Research Infrastructures NanoEnviCz (Project No. LM2015073), Pro-Nano- EnviCz (Project No. CZ.02.1.01/0.0/0.0/16_013/0001821) and the French-Czech Project PHC BARRANDE 2016 35785SC / 7AMB16FR004 supported by the Ministry of Education, Youth and Sports of the Czech Republic.***

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