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Characterisation and investigation of ion-implanted boron-doped single crystal diamonds as temperature sensor for ultra-precision machining

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Abstract
Ultra-precision machining is a crucial manufacturing process for the production of optical components in automotive, medical and aerospace industry and enables high dimensional accuracies and low surface roughness values. Dedicated single crystal diamond tools enable the manufacturing of optical and functional surfaces such as mirrors or lenses. Despite the high mechanical hardness, temperature induced chemical wear of the diamond tools occures during the process. To characterise und interpret the wear behaviour of diamond tools, the cutting temperature needs to be analysed. At state of the art, there are no precise methods available for analysing temperatures in the cutting zone of a single crystal diamond tool in order to identify the wear behaviour online during the process. Therefore, a dedicated measurement system based on boron-doped CVD single crystal diamonds as temperature sensor was developed. The electrosensory features of the fully boron-doped diamonds enable a direct temperature measurement in the cutting zone. To enable high sensitive temperature measurements, ion-implantation was used for partial and specific boron-doping close to the cutting edge of single crystal diamonds. To fundamentally evaluate the quality of the doping and contacting structures as well as the general process of the ion-implantation three different doping structures were investigated using single crystal diamond blanks prior doping the cutting tools. For this purpose, the boron-doped structures were optically characterised and the correlations between the resistances and the temperatures were evaluated as a function of different doping-levels and doping-lengths. First results show the successful application of the ion-implantation for boron-doping of single crystal diamonds. It could be proven that the selected boron-levels as well as boron-lengths lead to different initial conditions of the analysed specimens. Dedicated ion-implantation of single crystal diamond tools represents a promissing approach as highly sensitive temperature sensor.

Keywords: single crystal diamond, temperature sensor, ion-implantation, ultra-precision machining

1. Introduction

The optic and photonic industry is considered as a key technology for today and future applications in the fields of aerospace, medical and lighting technologies as well as in the area of automotive. This industry represents the driver for innovation and growth in the manufacturing sector and enables the increase of technological boundaries for a wide range of industrial applications. The requirements of optical systems concerning the shape accuracy a_s and surface quality are constantly increasing, which lead to further developments of the used process technologies. Ultra-precision machining with single crystal diamonds is mainly used for the manufacturing of optical components as well as highly complex optical systems. These diamond tools are typically characterised by a low rounded cutting edge radius in a range of $20\ \text{nm} \leq r_\beta \leq 50\ \text{nm}$, a radius waviness of $r_w \leq 250\ \text{nm}$ as well as a high hardness of $H_v = 10{,}000\ \text{HV}$ [1]. Despite the high mechanical hardness H_v, temperature induced chemical wear of the diamond tools occures during the process. According to the state of the art, temperature based chemical processes are the dominant wear mechanism of single crystal diamonds, which lead to a short tool life [2,3]. To characterise and interpret the wear behaviour of single crystal diamonds, the cutting temperature ϑ_c needs to be investigated with highly sensitive systems. Several research works focus on the development of precise methods for temperature measurement in the cutting zone [4,5]. At state of the art, there are no precise methods available for analysing temperatures ϑ in the cutting zone of single crystal diamond tools due to low measurement accuracies a_m and high response times t_r. For this purpose, a dedicated measurement system based on boron-doped single crystal diamonds as temperature sensor was developed. The doping enables electrosensory properties, which enables a direct temperature measurement in the cutting zone due to the correlation between the resistances R and the cutting temperatures ϑ_c. To enable high sensitive temperature measurements, ion-implantation was used for partial and specific boron-doping.

2. Experimental Setup

In order to prove the potential of ion-implantation, diamond blanks with different structures, doping-levels d_{lev} and doping-lengths d_{len} were investigated. For this purpose, diamond blanks with doping-levels of $d_{lev} = 5E^{13}$ - ions/cm², $d_{lev} = 3E^{14}$ - ions/cm² and $d_{lev} = 4E^{15}$ - ions/cm², doping-lengths of $d_{len} = 0.42$ mm, $d_{len} = 1.78$ mm and $d_{len} = 3.43$ mm as well as a constant doping-width of $d_w = 100\ \mu\text{m}$ and a doping-depth of $d_d = 145$ nm were used. For the characterisation of the ion-implantation, a highly sensitive measurement system for semiconductor applications type PA 200 of the company Suess MicroTec SE, Garching, Germany, was applied. Measurements of the resistances R and temperatures ϑ were done with a high-precision and temperature controlled wafertherm-chuck-system type SP 74 A of the company ERS Elektronik GmbH, Hagen, Germany. A suitable contacting of the diamond blanks could be realised with specific micro-manipulators, which enable a high position accuracy a_p for the measurements. The optical measurements of the doping-structures were carried out with the digital microscope type VHX-5000 of the company KEYENCE GMBH, Neu-Isenburg, Germany. Figure 1 shows the measurement setup (1a) and the three doping-structures, round (1b), rectangle (1c) and triangle (1d) with the contacting areas (gold).

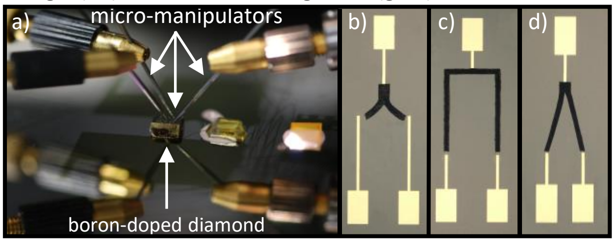

Figure 1. Measurement conditions with a) measurement setup and the doping-structures, b) round, c) rectangle and d) triangle

3. Experimental investigations

Within the investigations of the boron-doped diamond blanks, three different doping-levels d_{lev} and doping-lengths d_{len} were evaluated. To gain extensive knowledge about the potential of the ion-implantation, the initial resistances R_i as well as the resistance curves in dependence of temperature changes $\Delta\vartheta$ of each diamond blank were analysed. Figure 2 shows the findings of the initial resistances R_i by different doping-levels d_{lev} and doping-length d_{len} for a temperature of ϑ = 20 °C.

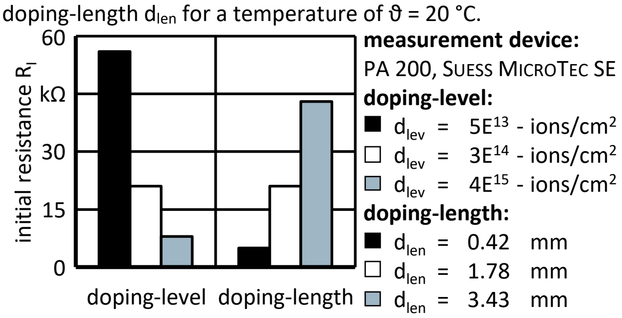

Figure 2. Interrelation of initial resistances R_I to doping-level and -length

The investigated diamond blanks show different resistances in a range of 17.25 kΩ ≤ R_I ≤ 56.33 kΩ in the initial state. The results of the investigation show a great influence concerning different doping-levels d_{lev} and doping-lengths d_{len} to the initial conditions of the diamond blanks. In general, using higher doping-levels d_{lev} and lower doping-lengths d_{len} result in reduced initial resistances R_I. According to the results, a correlation between the initial resistances R_I and the doping-levels d_{lev} as well as doping-lengths d_{len} could be proven. Additional experiments were carried out to show the general dependency between the resistances R and temperatures ϑ for the used doping-levels d_{lev} and doping-lengths d_{len}. The experiments were carried out with the highly sensitive measurement system type PA 200 and a temperature area of 20 °C ≤ ϑ ≤ 140 °C. Figure 3 illustrates the findings of the temperature measurements concerning three diamond blanks with different doping-levels d_{lev} by a doping-length of d_{len} = 1.78 mm.

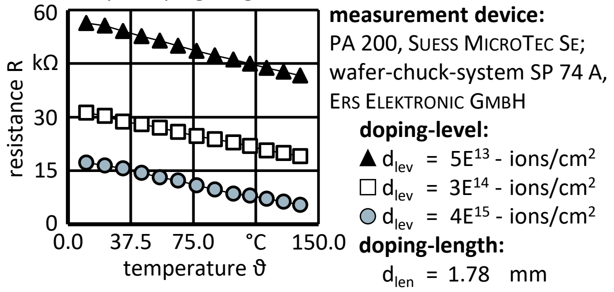

Figure 3. Resistance R over temperature ϑ for various doping-levels d_{lev}

All investigated diamond blanks show a comparable linear temperature behaviour with a specific offset. It could be determined that the resistances R decrease with increased temperatures ϑ with a minimum by the highest used temperature of ϑ = 140 °C for all investigated doping-levels d_{lev}.

According to the results, a negative temperature coefficient could be proven for ion-implanted boron-structures using single crystal diamonds. Figure 4 shows the influence of the temperature ϑ to the resistances R using three different doping-lengths d_{len} by a doping-level of d_{lev} = 3E^{14} - ions/cm^2.

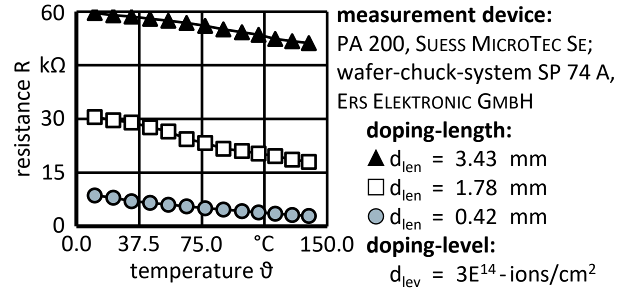

Figure 4. Resistance R over temperature ϑ by various doping-length d_{lev}

In general, the findings show a comparable temperature behaviour related to the investigation of the doping-level d_{lev}. Increased temperatures ϑ lead to reduced resistances R, whereby a negative temperature coefficient could also be proven. Using different doping-lengths d_{len} result in different initial resistances R_I, which show a defined offset behaviour in dependency to the changed temperatures ϑ. The lowest resistance R was obtained by a maximum temperature of ϑ = 140 °C and a reduced doping-length of d_{len} = 0.42 mm.

4. Conclusion

The findings show that the ion-implantation is suitable for the boron-doping of single crystal diamonds. Based on the investigations it could be obtained that the selected boron-levels d_{lev} as well as boron-lengths d_{len} lead to different initial conditions of the analysed specimens concerning the resistances R. According to the results, a great interdependency of the resistances R and the related temperatures ϑ could also be shown. Increased temperatures ϑ lead to reduced resistances R, whereby a negative temperature coefficient with a linear behaviour could be proven. All investigated specimens show a comparable temperature behaviour with a defined offset, which represent a process-reliable ion-implantation of single crystal diamonds. Furthermore, the ion-implantation shows a high flexibility for usable doping-structures regarding shape and size. Based on these scientific findings, the ion-implantation can be specifically selected for the cutting process and specific application areas, which results in a significantly higher sensitivity. This shows a great improvement compared to fully boron-doped single crystal diamond tools in past research works [6]. Further investigations address the qualification of ion-implanted single crystal diamonds as temperature sensors concerning measurement accuracy a_M and response time t_r.

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