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Schottky Contacts on Single-Crystal CVD Diamond

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Abstract – In this paper, a comparison of Gold, Nickel and Aluminium Schottky diodes fabricated on high-quality, Single-Crystal CVD Diamond is presented. Different metals, such as Gold, Nickel and Aluminium, have been deposited on the oxidised surface of an intrinsic diamond layer to serve as Schottky contacts, in order to investigate the physical properties of the different metal-semiconductor interfaces. A Cr-layer, followed by a subsequent Au deposition was used to form the Ohmic back contact for the Au-Schottky diodes, whereas a Cr-layer followed by a Ni deposition formed the Ohmic contact for the Ni and Al-Schottky contacts. Contacts have been characterized using I-V measurements. The gold Schottky contacts exhibited reverse leakage currents as low as 0.01μA at a reverse voltage of -600V, rising to 10 μA at 1kV (without any periphery protection). Nickel and Aluminium contacts exhibited lower reverse leakage currents and higher average breakdown voltages, whilst giving poorer forward conduction.

I. INTRODUCTION

Diamond is a promising material for high-power, high-frequency and high temperature electronics applications, where its outstanding physical properties can be fully exploited. It exhibits the highest energy-gap, carrier mobilities, breakdown field strength, and thermal conductivity of any wide band-gap material [1,2]. It could therefore produce the fastest switching, highest power density, most efficient electronic devices obtainable with applications in the RF power, automotive and aerospace industries. Lightweight diamond devices, capable of high temperature operation in harsh environments, could also be used in radiation detectors and particle physics applications [1, 3, 4] where no other semiconductor devices would survive [5,6]. In the past, research could only have been focused on polycrystalline and nano-crystalline material, due to the high cost of natural diamond and the lack of large single crystal synthetic diamond. The recent development of Single-Crystal CVD (SC-CVD) Diamond [1,3] has opened up the possibility of producing diamond electronic devices capable of replacing current silicon, silicon carbide and gallium nitride technologies in certain niche high-power and high-frequency markets. However, many physical and technological issues concerning this new material have yet to be addressed. Among them, the lack of a shallow n-type dopant at present had forced research to focus on unipolar p-type devices only, such as Schottky diodes and MESFETS, for RF [7,8] and high power applications. Successful n-type doping of diamond has recently been demonstrated [9], and bipolar devices on various crystal orientations have been reported to work at room temperature, whilst showing poor electronic properties [10,11].

II. EXPERIMENTAL WORK

An 18μm-thick, intrinsic SC-CVD diamond layer, homoepitaxially grown on a 300 μm-thick, heavily boron-doped – p-type – substrate has been used as a starting material. Prior to any further processing, the sample was cleaned using the following procedure: wipe with acetone; 10min solvent cleaning with isopropanol; 20 min refluxing in a saturated solution of sulphuric acid and potassium nitrate (1 g KNO_3 in 20 ml H_2SO_4), in order to Oxygen-terminate the surface. A 50 nm-thick Chromium layer, followed by a subsequent 200 nm-thick gold layer, were deposited on to the diamond sample, in an Edwards E306 coating system, under high vacuum (HV) conditions (1 x 10^{-6} mbar), to form the back (Ohmic) contact. The contact was then annealed in HV at 800°C for 10 min, at a pressure of 5×10^{-7} mbar, in order to form a layer of Chromium Carbide, which act as a more intimate contact, improving the specific

Fig. 1. Schottky contacts on the i-p+ SCCVD Diamond Sample.

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contact resistance [12]. Several 300 nm Schottky Au contacts, with a diameter of 650 µm, were deposited on the intrinsic layer. Figures 1 and 2 show a image of the sample, together with some of the basic process steps. Due to the early stages of the SC-CVD technology, material is still not available in satisfactory volumes, therefore it has been necessary to re-use the sample for the three metallization. Fabrication and characterization of Al and Ni diodes has been therefore carried out as follows. The Au-Schottky contacts were etched away from the top intrinsic layer using diluted aqua regia. The same acid etchant was used for stripping the back Au/Cr layer off. A new 80 nm-thick Cr-layer, followed by a 200 nm-thick Ni-layer contact was then deposited in order to make the Ohmic contact.

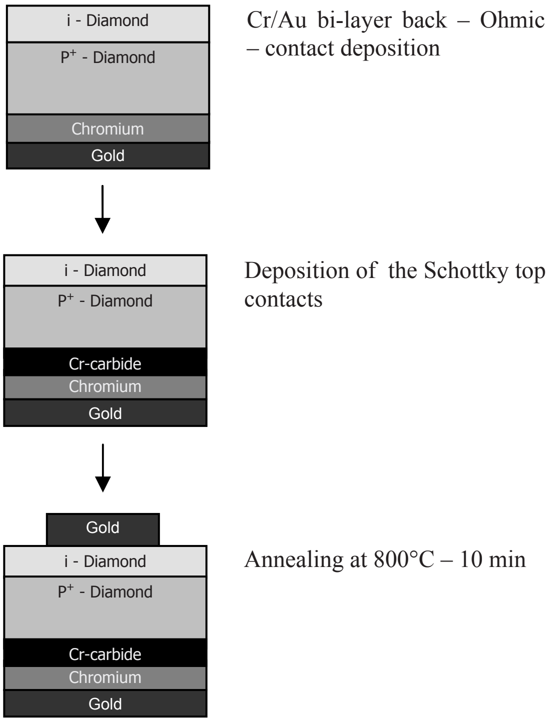

Fig. 2. Technological processes for the fabrication of SCCVD Diamond Au-Schottky Diodes

Several Nickel Schottky top contacts were then deposited using the same metal evaporation equipment used for the Au-contacts deposition. Finally, Al-Schottky contacts have been fabricated. No contact periphery protection was used in these experiments. After fabrication, each set of diodes were characterized by I-V measurements, using a Karl Suss probe station connected to an HP4142b measurement kit.

III. RESULTS

A. Reverse Bias

The reverse I-V characteristics, performed at room temperature, of two diodes of each of the three different Schottky metal contacts sets are plotted in Figure 3. The total set of Au-Schottky diodes (25 diodes) exhibited quite a homogeneous behaviour in reverse bias, with all the diodes exceeding a reverse blocking voltage of 600V, and a yield at ~1000V close to 40%. The reverse leakage currents, at a given voltage, are quite widely spread over the 25 diodes within a range of 4 orders of magnitude, showing average values of about 2×10^{-6}A at -500V. Reverse leakage currents reached values as low as 10^{-7}A at 600 Volts, for a device active area of 1.33×10^{-2}cm^2. A reverse blocking voltage of more than 1kV was found for some devices.

Almost all Ni-Schottky diodes exceeded 1kV, which was the limit of our measurement kit, and did not show any insurgence of breakdown at this voltage. The average leakage current densities were in the range of 5×10^{-5}A/cm^2 at a given voltage of -500V.

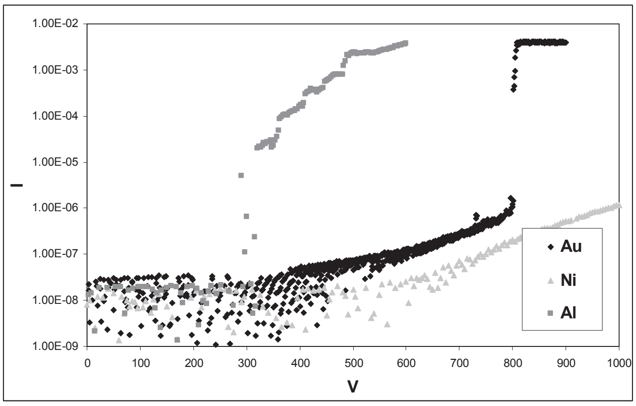

Fig. 3. Reverse characteristics of 3 fabricated Schottky diodes on single-crystal CVD diamond.

Al-Schottky diodes had an average leakage current density of about 1.5×10^{-4}A/cm^2 for the same reverse bias, but some diodes displayed an inhomogeneous behaviour at voltages higher than 500V, showing a sudden increase in the slope of the logarithmic plot of the current.

For all three metallization, current densities, at reverse bias approaching the reverse blocking capabilities of each diode, were quite high for a considerable percentage of the devices, and in the order of 5×10^{-2} A/cm^2.

B. Forward Bias

The forward characteristics, for the same diodes whose reverse current curves were previously plotted in Fig.3, are plotted in Fig. 4. As it is clear fromFig.4, diodes which had exhibited a reasonably good behaviour in reverse bias suffered from a poorer forward conduction. Though the Thermionic Emission theory does not strictly apply to these devices, a rough approximation of the Schottky Barrier Height - Φ_b – extracted from the semi-log I-V plot for the three metallizations is given. The better Au-Schottky diodes were able to reach a current density of 1A/cm^2, with a Φ_b of 0.98eV. Ni-Schottky diodes exhibit a lower current density, and have a comparable barrier height of 1.03eV, whilst Al diodes had barriers which varied among the contacts in a range between 0.85eV and 1.07eV.

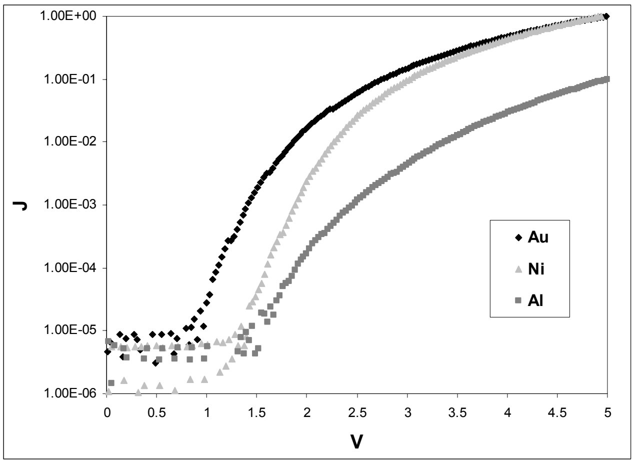

Fig. 4. Semi-log plot of the Forward current density of the diodes

IV. DISCUSSION

Although metals with very different work functions have been used in this study, the related Schottky barrier heights Φ_b barely changed. This behaviour is probably due to the presence of an interfacial layer between the top metal contact and the i-layer of the diamond sample. Oxygen from the cleaning procedure, or from the atmosphere, has created a semi-insulating layer, several atomic layers thick. It has been shown that this layer can be physically desorbed during annealing (further results will be reported on a future publication). This high density of surface states have the effect of "pinning" the barrier height, as explained by the Bardeen model (1947) [2].

TABLE I

SCHOTTKY BARRIER HEIGHT, Φ_b, FOR THE DIFFERENT SCHOTTKY DIODES

	Φ_b (eV)
Au	0.98
Ni	1.07
Al	1.16

The low current density levels in forward mode arise from the intrinsic – doping concentration <10^{13}cm^{-3} – 18μm-thick top layer, which gives rise to a very high specific on-resistance. The simple Mott-Gurney law:

$$J = \frac{9}{8}\varepsilon_r \varepsilon_0 \mu \frac{V^2}{L^3} \qquad (1)$$

with J the current density, and L=18μm, theoretically gives 9 A/cm^2 for our structure, but it does not take in to account any carrier diffusion and the Ohmic losses. Ni and Al-Schottky diodes, fabricated using a Ni/Cr-layer to serve as the back contact, might also suffer from a higher specific contact resistance as a thin Ni-Chrome alloy might have formed upon deposition of the Cr/Ni back contact, giving a layer with higher resistivity. These assumptions need further investigation. The wide spread of values for the current, both in forward and in reverse, within the same batch of diodes can be explained by the presence of inhomogeneities in the Metal/Diamond contacts [13]. This phenomenon can be due to both the deposition process and the sample preparation itself. The cleaning procedure might also be partly responsible. The lack of any periphery protection for the Schottky contact is partly responsible for the increase in the leakage current, due to Electric field enhancement at the edge, which, in turn, lowers the barrier height, thus producing the increase in reverse current shown in Fig.3.

V. CONCLUSION

In this paper, vertical Schottky diodes on to a i-p+ Single-Crystal CVD Diamond sample, using different metals – Au, Ni, Al – as Schottky contacts, and different stacking layers – Cr/Au, Cr/Ni – for the back, Ohmic contact, have been fabricated and electrically characterized using I-V measurements. The uniformity of the barrier heights for different metallizations suggests the presence of an interfacial layer, whereas the rather high reverse leakage currents are suggested to be due to the lack of an edge termination. Current density has been shown to be mainly dependent on the resistivity of the intrinsic diamond layer.

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