Influence of Electrical Contacts on the Performance of Diamond Radiation Detectors

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Research, Development and Production:

- High Energy Physics
- Nuclear and Environmental Monitoring
- Radiotherapy Dosimetry
- Deep UV Detection
- Space and Astronomy
## Intrinsic Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Natural Diamond</th>
<th>CVD Diamond</th>
<th>Potential device application benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.1</td>
<td>3.2</td>
<td>3.44</td>
<td>5.47</td>
<td>5.47</td>
<td>High temperature</td>
</tr>
<tr>
<td>Breakdown field (MVcm(^{-1}))</td>
<td>0.3</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>High voltage</td>
</tr>
<tr>
<td>Electron saturation velocity (x10(^7) cm s(^{-1}))</td>
<td>0.86</td>
<td>3</td>
<td>2.5</td>
<td>2</td>
<td>2</td>
<td>High frequency</td>
</tr>
<tr>
<td>Hole saturation velocity (x10(^7) cm s(^{-1}))</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Electron mobility (cm(^2) V(^{-1}) s(^{-1}))</td>
<td>1450</td>
<td>900</td>
<td>440</td>
<td>200–2800</td>
<td>4500</td>
<td></td>
</tr>
<tr>
<td>Hole mobility (cm(^2) V(^{-1}) s(^{-1}))</td>
<td>480</td>
<td>120</td>
<td>200</td>
<td>1800–2100</td>
<td>3800</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (Wcm(^{-1}) K(^{-1}))</td>
<td>1.5</td>
<td>5</td>
<td>1.3</td>
<td>22</td>
<td>24</td>
<td>High power</td>
</tr>
<tr>
<td>Johnson’s figure of merit</td>
<td>1</td>
<td>410</td>
<td>280</td>
<td>8200</td>
<td>8200</td>
<td>Power-frequency product</td>
</tr>
<tr>
<td>Keys’s figure of merit</td>
<td>1</td>
<td>5.1</td>
<td>1.8</td>
<td>32</td>
<td>32</td>
<td>Transistor behavior thermal limit</td>
</tr>
<tr>
<td>Baliga’s figure of merit</td>
<td>1</td>
<td>290</td>
<td>910</td>
<td>882</td>
<td>17200</td>
<td>Unipolar HF device performance</td>
</tr>
</tbody>
</table>

Diamond tetrahedron

(from ww.pdymorf.net/matter14.htm)
Figure 2-11: Cross-section of a 100 μm-thick CVD diamond film grown by DC arc jet. The columnar nature of the growth is clearly evident, as is the increase in film quality and grain size with growth time. (from http://www.chm.bris.ac.uk/pt/diamond/semflat.htm)
**First Radiation Detectors (1945)**

**From Natural Diamond**

At that time counting properties were found to be uncontrollable, depending upon the crystal and the type of radiation.

• Furthermore, charge polarization occurred, leading to a progressive reduction in both counting rate and pulse amplitude as a function of the time of irradiation.

• R. HOFSTADTER., Phys. Rev. 73 (1948) 631.

• Since 1970, the attractive properties of diamond for radiation detection were demonstrated by KOZLOV et al. from monocrystalline diamond stones of extremely high electronic quality.
Figure 2-24: $^{241}$Am detection spectra recorded on 4 grades of natural and CVD diamond [Ber01] Bergonzo et al., *Diamond and Related Materials*, Volume 10, Issues 3-7, March-July (2001), 631-638
Device Fabrication Issues

1. Mechanical Adhesion of the Contact
   (the flatter the surface -> less adhesion)

2. Good Injecting Contacts, Polarization Free
   (high work function metals, B doped layer)

3. Stability, Reproducibility, Durability
### Difficulty in mechanical adhesion

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>12,01</td>
<td>28,09</td>
</tr>
<tr>
<td>Density $\rho_m$ (g cm$^{-3}$)</td>
<td>3.52</td>
<td>2.33</td>
</tr>
<tr>
<td>N. Atoms $N_A$ (x10$^{22}$ cm$^{-2}$)</td>
<td>17.7</td>
<td>4.96</td>
</tr>
<tr>
<td>Atomic Distance $\ell_A$ (Å)</td>
<td>1.54</td>
<td>2.35</td>
</tr>
<tr>
<td>Fusion $T_F$ (°C)</td>
<td>4100</td>
<td>1420</td>
</tr>
<tr>
<td>Work function $\Phi$ (eV)</td>
<td>4.81</td>
<td>4.58</td>
</tr>
<tr>
<td>bandGap $E_g$ (eV)</td>
<td>5.5</td>
<td>1.12</td>
</tr>
<tr>
<td><strong>Electrical Breakdown</strong> $E_B$ (V/cm)</td>
<td>$10^7$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Resistività $\sigma$ (Ω cm)</td>
<td>$&gt;10^{11}$</td>
<td>2.3 $\times 10^5$</td>
</tr>
<tr>
<td>Densità intrinseca portatori (cm$^{-3}$)</td>
<td>$&lt;10^3$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Mobilità degli elettroni (cm$^2$V$^{-1}$s$^{-1}$)</td>
<td>1800</td>
<td><strong>2200</strong></td>
</tr>
<tr>
<td>Mobilità delle lacune (cm$^2$V$^{-1}$s$^{-1}$)</td>
<td>1200</td>
<td>480</td>
</tr>
<tr>
<td>Costante dielettrica</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Energia di coesione atomica (eV/atom)</td>
<td>7.37</td>
<td>4.63</td>
</tr>
<tr>
<td>Conducibilità termica (Wm$^{-1}$K$^{-1}$)</td>
<td>1000-2000</td>
<td>150</td>
</tr>
<tr>
<td>Energia di creazione di una coppia $e$-h (eV)</td>
<td>13</td>
<td>3.6</td>
</tr>
</tbody>
</table>

### Difficulty in making Ohmic Contact

- Low Leakage current
- No Cooling Needed

### High Radiation Hardness
Device Fabrication

• One of the problems encountered when manufacturing semiconductor devices in diamond is the fabrication of low resistance ohmic contacts.
• Historically, there have been three main approaches to solve this problem and lower the resistivity of the contact:

1. Damaging the diamond surface in order to disrupt the sp$^3$ bonding.

2. Using carbide forming metals like titanium or chromium, that create an hybrid metal-diamond interface material.

3. Doping of diamond during growth or using ion implantation.
**Polarization free contacts**

- It has been observed that polarization phenomena occur when electric currents pass through an insulator crystals.

- The bandgap of diamond being large, and the resistivity extremely high the same situation occurs here.

- **If the electrical contact is not able to extract and inject electrons fast enough**, then the neutrality of the crystal after the passage of ionizing nuclear radiations is not restored in the time interval between two consecutive events.

- As a result, charge accumulation occurs within the crystal. Immobile carriers establish an electric field which acts in a direction opposite to the applied field produced by the external bias voltage $V$. 
## Contacts Used on Polarization Free Diamond Detectors

<table>
<thead>
<tr>
<th></th>
<th>Injecting</th>
<th>Electrons</th>
<th>Blocking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Holes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>painting, followed by heating in air to 500-700°C for 2-3 hours.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>electroless, followed by heating in air 500-700°C for 10 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>aquadag, followed by heating in vacuum to 500-700°C for 2-3 h.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>heating to 1000-1300°C under 0.1 torr air pressure for 30 min. (graphitization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Holes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>as for hole injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Blocking</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>vacuum deposition by evaporation sometimes the surface is graphitized by heating to 1000-1300°C und. reduced air pressure (0.1 torr).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>ion implantation: dose below $10^{15}$ cm E-2, annealing in vacuum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>800-1200°C, energy impl. 40-100 keV.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td>ion implantation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Influence of Grain Boundaries on the Performance of Diamond Detectors
Figure 5-11: Comparison between BSE and CL image of the inter-digitated diamond sensor DF3 fabricated from high quality diamond film where the average crystallite dimension is approximately 100 μm. The image was taken of the growth surface of the film, which was polished. The device has a 100 μm inter-electrode gap and a 100 μm electrode width.

Figure 2-25 Diagram of lateral charge drift, typical of a coplanar detector with inter-digitated electrodes.

Figure 2-26. Calculated electric field profiles; 100 um pitch, 50 um gap [Sel01].

Figure 5-12: Comparison between cathodoluminescence and BSE image of regions of high quality diamond material (detector DF3). Three large crystallites are indicated by the boxed regions.
Figure 5-18: IBIC image of one of the largest crystallites identified in the device DF3
Figure 5-17: single crystallite spectrum, detector DF3.

Ion Beam Induced Charge (IBIC) Single Crystallite Spectrum

Figure 5-20: pulse height spectra extracted from four regions in the crystallite, corresponding to (A) an area of maximum charge signal in the centre of the crystallite, (B) an area towards the edge of the crystallite, (C) and (D) areas outside the crystallite, as indicated in Figure 1.

1 µm diameter focussed beam of alpha particles

Influence of Metal-Diamond Interface on the Performance of Diamond Detectors
The RC time constant associated with contact resistance can limit the frequency response of devices. The establishment of a contact fabrication methodology is a critical part of the technological development of any new semiconductor. Electromigration and delamination at contacts are also a limitation on the lifetime of electronic devices.
FIG. 7. Interface band diagrams of titanium on diamond; (a) as-deposited titanium on diamond, (b) high concentration of electrically active defects, which are created via the formation of a carbide and/or ion bombardment, reduces the depletion width and increases the tunneling current, (c) the electrically active defects created as in (b) decrease the effective barrier height.
Influence of metal–diamond interfaces on the response of UV photoconductors

(a) Au

(b) Ti-Au

(c) Cr-Au

(d) Al-Au
Influence of metal–diamond interfaces on the response of UV photoconductors

- Cr 4.5 eV
- Ti 4.3 eV
- Al 4.1 eV
- Au 5.1 eV
- Diamond 4.8-5.8 eV
Diamond Work Function

- Hydrogen chemisorbed diamond surface showed a minimum work function value of 4.8 eV.
- Oxygen chemisorbed diamond surface, which showed a maximum work function value of 5.8 eV.
- The surface potential value, which corresponds to the surface work function value, was strongly influenced by the species of the chemisorption on the diamond surface.
- The surface work functions were strongly correlated with the surface electronic states.
- A change of the chemisorbed species on the surface sensitively affected the surface work function.

When two metals are electrically isolated from each other, an arbitrary potential difference may exist between them. However, when two different metals are brought into contact, electrons will flow from the metal with a lower work function to the metal with the higher work function.

If two metals having differing work functions are touched together, one steals electrons from the other, and the opposite net charges grow larger and larger; this is the Volta effect. The process is halted when the voltage between the two metals reaches a particular value (the difference in work function values; usually less than one volt.)

If metal touches a semiconductive material, or if two different semiconductors are placed into contact, one becomes charged slightly positive and the other slightly negative. It is found that if this junction between semiconductors is connected to a power supply, and if the power supply is set to a voltage slightly higher than the natural voltage appearing because of contact electrification, then for one polarity of voltage there will be a current between the two semiconductor parts, but if the polarity is reversed, the current stops.
Influence of metal–diamond interfaces on the response of UV photoconductors.
Chromium-Au Contacts
30 kVp X-ray Response

Graphitised-Boron Doped Contacts


Figure 4-13: Phase Contrast Microscopy Image, BG devices
Graphitised-Boron Doped Contacts
30 kVp X-ray Response

Graphitised-Boron Doped Contacts
30 kVp X-ray Response

I-V Characteristic

0642615-52  I-V plot DDL1, Cr/Au, TiW Contacts
From +200 Volts we have 100% Charge Collection Efficiency for a sample thickness of 530 um. Saturation E-field: 200 V / 530 um. E-field = 0.377 V/um.
Single Pulse under Am-241
5.5 MeV \(\alpha\)-particles

SC-Diamond Detector Pulse using slow electronics (300MHz)

In Collaboration with University of Huelva-CNA Sevilla

Arnaldo Galbiati
Response under Am-241
5.5 MeV $\alpha$-particles

Amplitude Histogram Response using Am241 (5.5MeV)

In Collaboration with University of Huelva-CNA Sevilla
Response under Am-241
5.5 MeV α-particles

Area Distribution for the 500um SC-Diamond Detector

In Collaboration with University of Huelva-CNA Sevilla
UV Response (Cr/Au contact)

D12-26 (Cr/Au interdigitated) UV response at 283 mA
UV Response
(Cr/Au contact)

D26 Cr/Au interdigitated UV response at -50 Volts 283 mA

Lamp On
982 nA

Lamp Off

0.49 nA

Successive Measurements (~1 second)

Current (nA)
UV Response
(TiW contact)

UV TiW interdig 222 mA 22.05.08
Next positive biases were applied (500V, 250V, 100V, 50V, 10V). For these biases the sample showed very good behavior under irradiation. For example, considering a bias of 100V the sample shows very fast response while the source is switched on/off, absence of priming effect and very low fluctuation of the signal (that is below 0.5%). The signal to noise ratio is very high and about S/N $\sim 3.3 \times 10^4$.

The response velocity of the sample was checked recording the data every 0.2 seconds. It is possible to see that when the source is switched on the sample reach the stabilization in a time that is less then 0.2 seconds.

In Collaboration with Krakow IFJ PAN
In Collaboration with Krakow IFJ PAN
To check the repeatability of the signal, one measurement was repeated several times at the same operating conditions. Each measurement in this case lasts one minute with a break of about 10 seconds. Taking the integral of each pulsed irradiation and averaging the values of area a coefficient of repeatability below 0.5% was found.

In Collaboration with Krakow IFJ PAN

DDL Contact
Radiotherapy Dosimetry
Co 60 Response

Repeatability

@100V
Dose rate linearity

Current (A) vs Dose Rate (Gy/min)

@100V

In Collaboration with Krakow IFJ PAN
Conclusions:

We have a different device according to the metallization used!