Diamond device fabrication and characterization

Silvio Sciortino, Stefano Lagomarsino, Giuliano Parrini
INFN and Department of Physics of Florence
GSI Darmsadt

Arianna Morozzi, Keida Kanxheri, Daniele Passeri, Leonello Servoli
INFN and University of Perugia

• Overview of silicon-diamond bonding

• Laser graphitization studies: transient current measurements induced by femtosecond laser
Activities in the framework
• of the experiment 3D_SOD of italian INFN
• and the Diamond Detectors WP of the Detector Technology and System Platform (Helmoltz Association)

• **INFN and Univ. of Florence**: Laser-bonding of Si chips to diamond (SOD), laser graphitization for 3 D detectors (Stefano Lagomarsino* talk)
  *supported by GSI for 2014-2015

• **INFN an Univ. of Perugia**: development and/or procurement of Si chips, simulations, characterization of detectors (Keida Kanxheri, next talk)
• Overview of silicon-diamond bonding

We are trying to implement two concepts:

Chip-On-Diamond

MAPS-On-Diamond

an idea of G. Parrini
MAPS-On-Diamond. Sample used for preparing the device

- 5.0 x 5.0 x 0.5 mm³ pCVD electronic grade E6 samples
- 4.5 x 4.5 x 0.5 mm³ scCVD electronic grade E6 samples

5 x 5 mm² RAPS03 Monolithic Active Pixel Sensor On Diamond thinned to 20 and 25 µm

- 256x256 pixel matrix (10x10 µm)
- Four 128x128 submatrices.
- Two submatrices have a small Photodiode: 4% of pixel surface) to minimize the sensing capacitance
- The other two have a large photodiode (77% of the pixel surface) to maximize the sensing area.
- The estimated effective diffusion region is below 30 µm;
For SOD bonding the surfaces must be polished and in contact before laser processing. We choose the best polished pCVD diamond surfaces.

Under this condition a uniaxial pressure of 800 atm is needed for adhesion before laser bonding.

355 nm, 20 ps, 0.4 J/cm²
Unfortunately the RAPS thinned surface is rough.

RAPS thinned @ 25 & 20 µm

Backside profilometry

$R_a \sim 4 \text{ nm}$

Peak to peak $\sim 50 \text{ nm}$
We also take into account the pattern of the RAPS electronics. Using a gold buffer to make the pressure more uniform.
RAPS thinned @ 25 µm bonded on pCVD diamond (SOD_40)  

RAPS thinned @ 25 µm bonded on scCVD diamond (SOD_44)  

RAPS thinned @ 20 µm bonded on scCVD diamond (SOD_45)  
In preparation
Adhesion Interface seen through diamond

Without Au buffer
Bad adhesion, interference fringes

Au buffer, still we have powder contamination, a class 100 clean chamber is needed
CONCLUSIONS

25 µm RAPS bonded to diamond successfully (almost) all the matrix sensors working

Adhesion must be optimized
- Better polishing needed (present technology allows ultraflat surfaces at the atomic level*)
- Use of a class 100 clean chamber

We must increase the statistics of tested devices
- 10 pCVD diamond samples from II-VI delivered at the end of the year
- We can fabricate and test one new device per month

Yatsui T. et al. Univ. of Tokyo
Laser graphitization studies:

transient current measurements induced by femtosecond laser, an experimental study aimed at understanding the physics of graphitization.

A deeper understanding of the process will be useful to predict the outcome at different process parameters (wavelength, intensity, pulse width, repetition rate) and to plan useful improvements of the technology.
• Lower current detectable 0.4 µA, higher current induced by laser 3 mA
TCT measurements with alpha particles

Standard TCT measurements were carried out to evaluate the TCT setup performances on a monocrystalline scCVD diamond sample prepared, metallized and tested under care of the Target and Detector Laboratories of GSI, in particular, Michael Traeger, Annette Huebner and Robert Visinka.
\[ v = \frac{\mu E}{\left(1 + \left|\frac{\mu E}{v_{\text{sat}}^n}\right|^n\right)^{\frac{1}{n}}} \]

\[ n \approx 1 \]
\[ \mu_e = 2380 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \]
\[ v_{\text{sat}_e} = 1.44 \times 10^7 \text{ cm/s} \]

\[ n \approx 1 \]
\[ \mu_h = 2170 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \]
\[ v_{\text{sat}_h} = 9.52 \times 10^6 \text{ cm/s} \]

In the range reported by: M. Pomorski, E. Berdermannet al., Diamond Relat. Mater. 16 (2007) 1066–1069.

TCT measurements with alpha particles
(Am-241 source)
4.5 MeV after 1 cm in air, about 55 fC generated in diamond

K. N. Yu, C.W.Y. Yip, D. Nikezic, J.P.Y. Ho, V.S.Y. Koo,

\[ i(t) = Q_0 \frac{v}{d} e^{-\frac{t}{\tau}} = \frac{Q_0}{T} e^{-\frac{t}{\tau}} \]

- \( d = \) thickness
- \( T = \) transit time
- \( \tau = \) lifetime
TCT measurements with alpha particles

\[ Q(t) = \int_0^T \frac{Q_0}{T} e^{-\frac{t}{\tau}} dt = Q_0 \frac{\tau}{T} \left( 1 - e^{-\frac{T}{\tau}} \right) \]

\[ Q(t) \approx Q_0 - Q_0 \frac{T}{\tau} \]

electrons:
\[ Q_0 = 60 \text{ fC}, \]
\[ \tau = 50 \text{ ns} \]

holes:
\[ Q_0 = 58 \text{ fC}, \]
\[ \tau = 375 \text{ ns} \]
**TCT measurements with pulsed laser source**

30fs mode-locked Ti-sapphire laser

(peak at 800 nm, photon energy: 1.56 eV)

Repetition rate 1 kHz

Laser energy per pulse: 0-4 µJ, focus area 50 µm

0-8 J/cm² per pulse,

pulse power $2.5 \times 10^{14}$ W/cm², field strength $2.3 \times 10^{12}$ V/m

below the graphitization threshold at least in the bulk

Single crystal “electronic grade” scCVD

Electrodes made by superficial graphitization as a raster of columns with a 8 ns, Q-switched Nd:YAG laser

Next sample, should be equipped with standard metallizations for both alpha and laser measurements
The transit time $T$ increases from 25 ns to 1.2 $\mu$s as the energy per pulse goes from 0.1 $\mu$J to 4 $\mu$J.

This is due to the high density of the plasma generated by the field and the mutual attraction of the holes and electrons.

A typical current transient shape is shown in figure at a voltage bias of 500 V.

The rising part of the current waveform can be fitted to a $\sqrt{t}$ trend and the decaying part to a $\sqrt{(t-T)}$ curve (with different proportionality constants).
Phenomenological model devised to explain the current waveforms (S: Lagomarsino)

\[ E_0 \text{ (externally applied physics)} \]

\[ \rho_{\text{ext}} \ll \rho_{\text{ext}} \]

\[ E \approx 0 \]

\[ E = E_0 + \text{field of the space charge} \]

The evolution of the plasma ball is ruled by two kinds of process:

- Diffusion
- Electric field → drift current → space charge distribution
Moreover, since the transit time $\ll$ evolutionary time of the plasma ball, we can adopt a quasi-stationary approximation.

\[
\frac{d}{dR} R^2 = D - \frac{\mu \varepsilon E_0^2}{d 2 \pi \zeta \rho + \rho_0} \frac{1}{\rho}
\]

\[
\frac{1}{\rho} \frac{d}{dt} \rho = -\left( \frac{1}{\tau} + \frac{3D}{2R^2} \right)
\]

$R$ radius of the plasma ball

$\tau$ is a lifetime of plasma $\sim 190$ ns
Experimental plot of the carrier density vs. the energy of the pulse in a Log-Log scale. The trend before $1 \, \mu J$/pulse is that of a more-than-fourth power law, demonstrating a combinations of multi-photon ionization processes.

$$\text{carrier density} = C_0 \times (\text{energy per pulse})^m$$

$$C_0 = 10^{19} \quad m = 4.4$$
Good qualitative agreement with the theoretical model of excitations presented by Tzveta Apostolova (this workshop)
Conclusions

- Order of the process 4 and five multiphoton excitation determined experimentally
- The excitation theoretical model is in order-of-magnitude agreement showing that we catch the relevant physics of the process
- We successfully modeled also the decay of the laser induced plasma after the pulse
- Measurements up to the graphitization threshold
- Refinement of the theoretical model (Tzveta Apostolova) to predict the carrier density required for phase transitions
- In a good track for fully understand the graphitization process in diamond
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Thank you for listening!