

Locally ion Implantation and annealing effects in Diamond

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DE LA RECHERCHE
ET DE L'INNOVATION

Attractive electronic properties of diamond

- wide band gap
- high breakdown voltage
- high charge carrier mobility

- good thermal conductivity
- robustness
- n and p doping

- ...



		Si	4H-SiC	GaN	Ga ₂ O ₃	Diamond
Bandgap E_G [eV]		1.10	3.20	3.45	4.9	5.47
Saturation drift velocity v_S [$\times 10^7$ cm/s]	Electron	1.1	1.9	2.5	2	2.5, 1.9 [5]
	Hole	0.8	1.2	-	-	1.0, 1.4 [5], 0.6 [6]
Carrier mobility μ [cm^2/Vs]	Electron	1500	1000	1500	300	4500 [1],
	Hole	450	120	200	-	3800 [1], 2000 [7]
Breakdown field E_{max} [MV/cm]		0.3	2.8	5	8	10–22, 9.5 [8]
Dielectric constant ϵ_r		11.9	9.66	8.9	9.93	5.7
Thermal conductivity λ [W/mK]		150	490	130	23	2200
Baliga's figure of merit (BFOM) $\epsilon_r \mu E_{max}^3$		1.0	440	2950	3516	473078 (3380)
Baliga's high frequency FOM (BHFOM) μE_{max}^2		1.0	58	237	158	12510 (1486)
Huang's temperature FOM (HTFOM) $\lambda / \epsilon_r E_{max}^2$		1.0	0.43	0.07	0.01	0.46 (0.97)
Huang's chip area FOM (HCAFOM) $\epsilon_r \mu^{1/2} E_{max}^2$		1.0	58	192	280	3887 (226)

H. Umezawa, *Materials Science in Semiconductor Processing* 78 (2018) 147–156

Promising applications



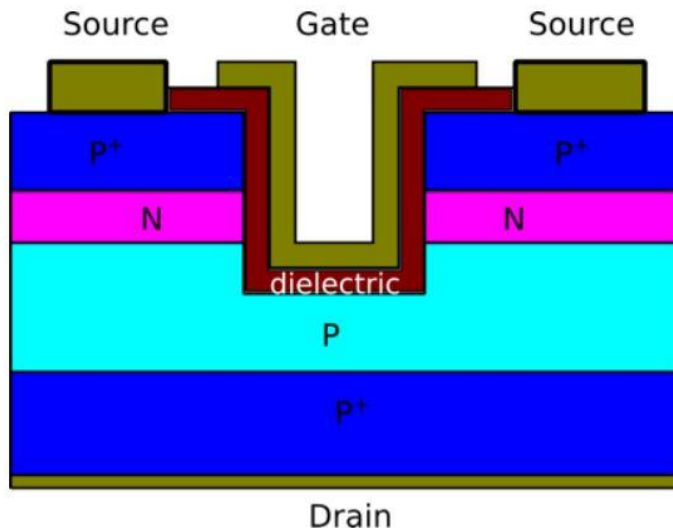
- **Power electronics**
- High frequency devices
- UV emitting diodes
- Quantum applications
- Sensors
- ...



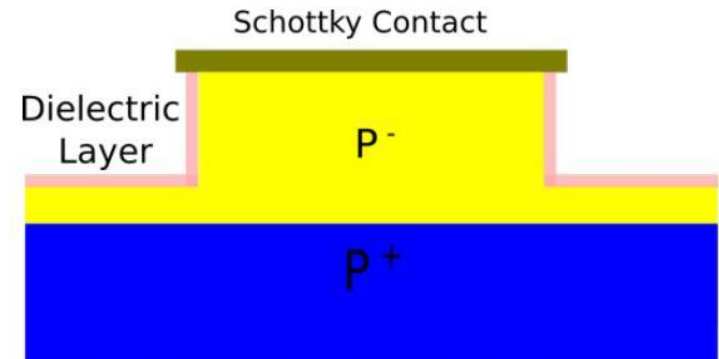
Some challenges related to doping

Growth of layers stack with various doping
Overdoping of diamond
Localized doping
...

UP-power MOSFETs



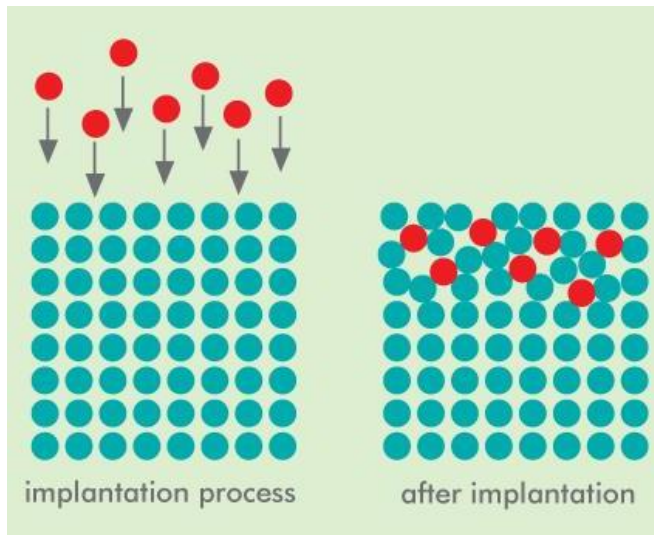
TMBS Diodes



Doping by ion implantation

➤ Local over-doping
for ohmic contacts

➤ Localized doping
for junction termination extension



Ion implantation:

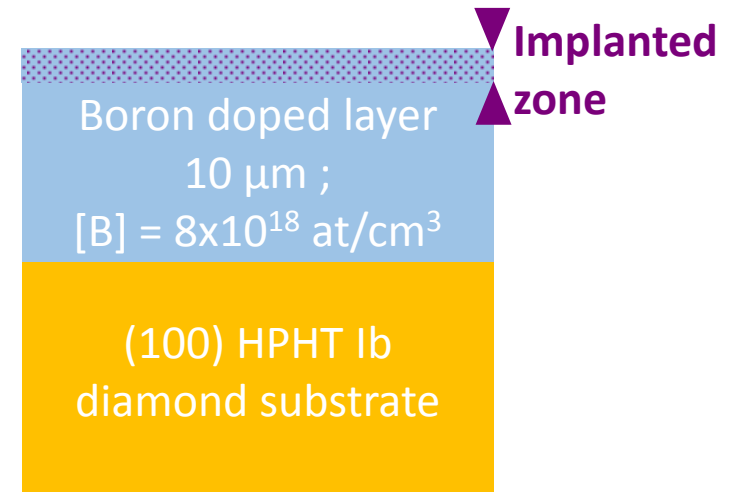
- allows to introduce atoms in the crystal but also defects as vacancies
- requires an annealing to recover cristallinity and activate dopants

Our experimental protocol

Boron implantation of a p-type diamond homoepilayer

by selecting conditions to obtain a vacancy level lower than 10^{22} at/cm³ and avoid graphitization

Implantation	Step	Energy (keV)	Dose (at/cm ²)
Beam Line: ¹¹ B, Tilt 7°, 500°C	1	90	7.5×10^{14}
	2	55	4.5×10^{14}
	3	24	3.5×10^{14}
	4	9	2.0×10^{14}
PIII: BF ₃ , Tilt 0°	5	4	3.0×10^{14}



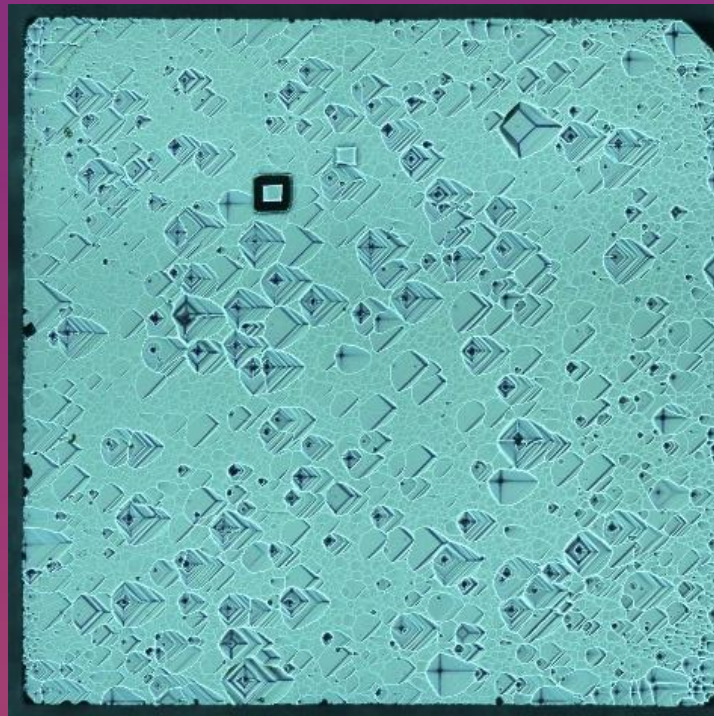
on which are performed

Structural (SIMS, TEM, AFM) & **Electrical** (4 probes, Hall, TLM)
experiments

As implanted & annealed

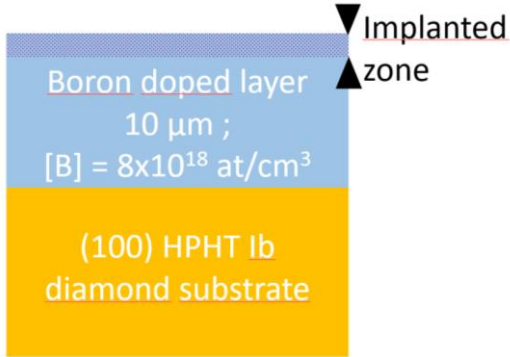
(1700°C, 30 min, Ar)

Structural results

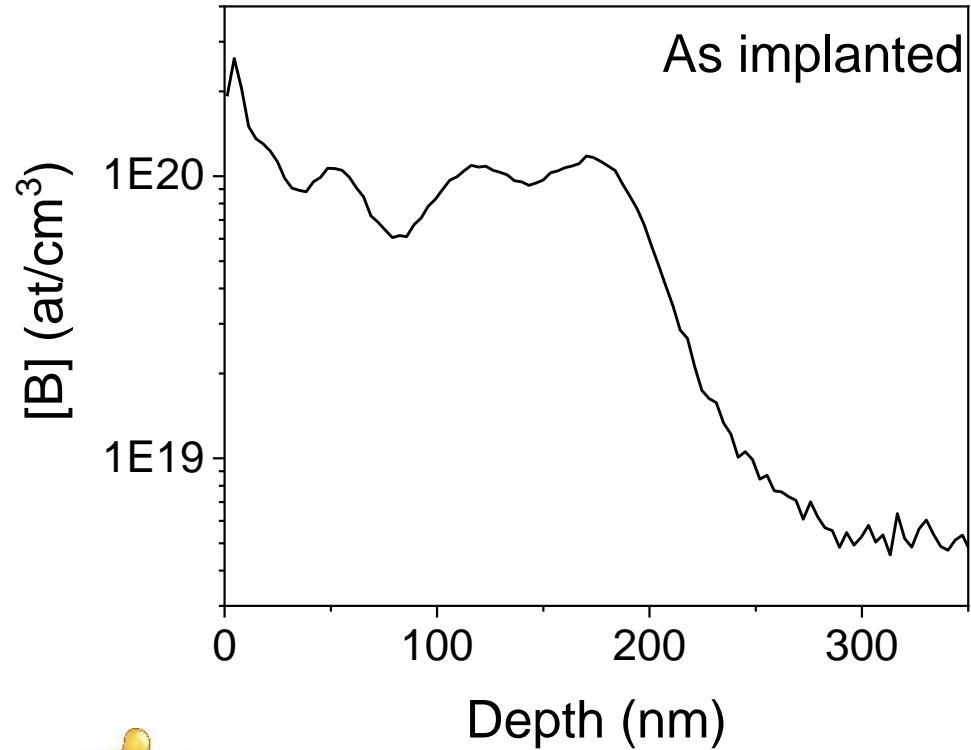


~ 3 mm

As implanted: ~ 200 nm of implanted zone



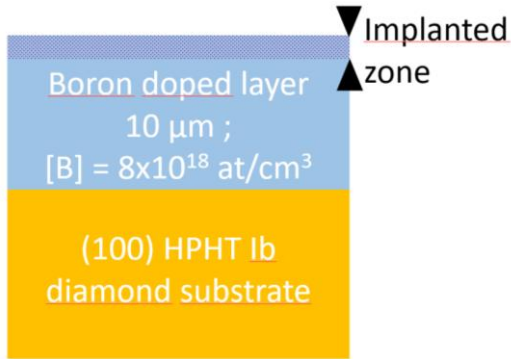
SIMS profil



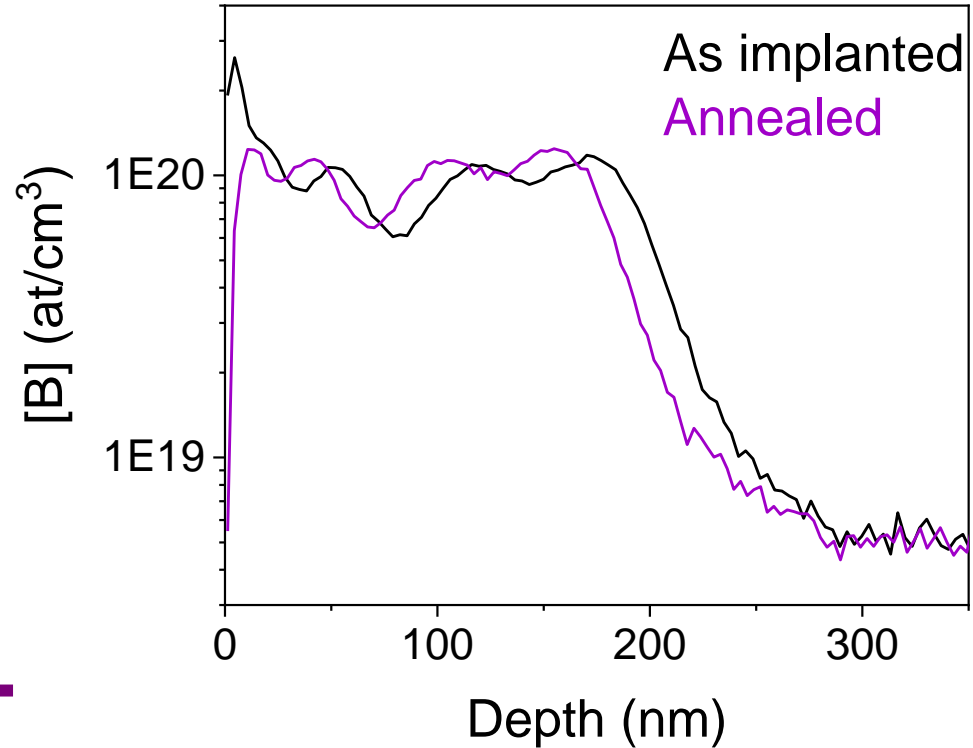
5 implanted steps observed

Implantation	Step	Energy (keV)	Dose (at/cm ²)
Beam Line: ¹¹ B, Tilt 7°, 500°C	1	90	7.5x10 ¹⁴
	2	55	4.5x10 ¹⁴
	3	24	3.5x10 ¹⁴
	4	9	2.0x10 ¹⁴
PIII: BF ₃ , Tilt 0°	5	4	3.0x10 ¹⁴

Annealed: ~185 nm of implanted zone



SIMS profil

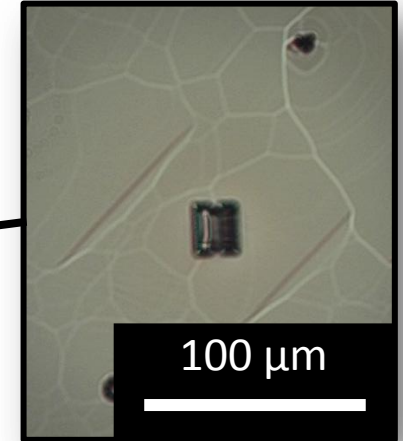
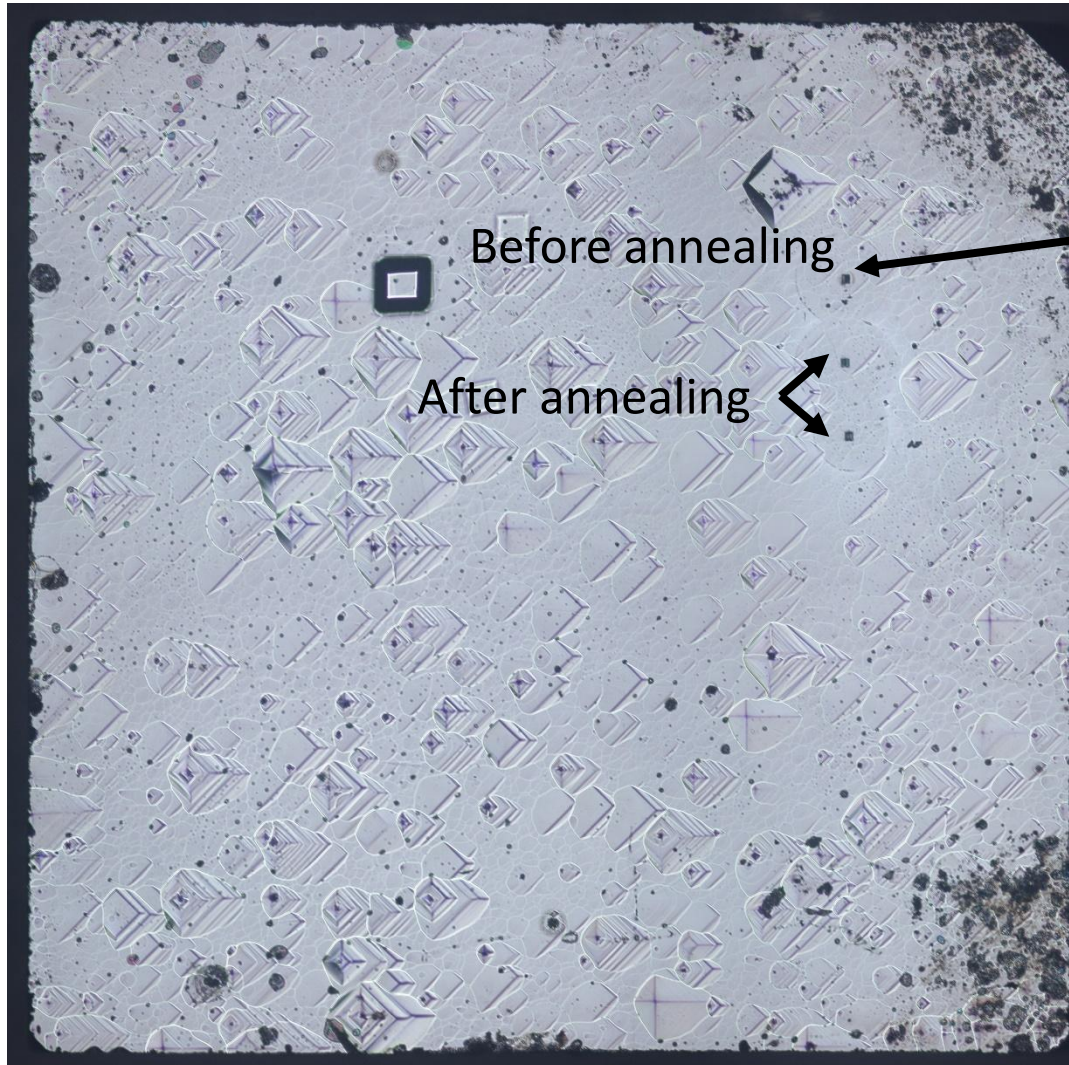
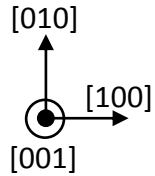


Shift of the profil

→ Etching of ~15 nm (loss of step 5)

Implantation	Step	Energy (keV)	Dose (at/cm ²)
Beam Line: ¹¹ B, Tilt 7°, 500°C	1	90	7.5x10 ¹⁴
	2	55	4.5x10 ¹⁴
	3	24	3.5x10 ¹⁴
	4	9	2.0x10 ¹⁴
PHI: BF ₃ , Tilt 0°	5	4	3.0x10 ¹⁴

Cross sections for TEM in the implanted zone



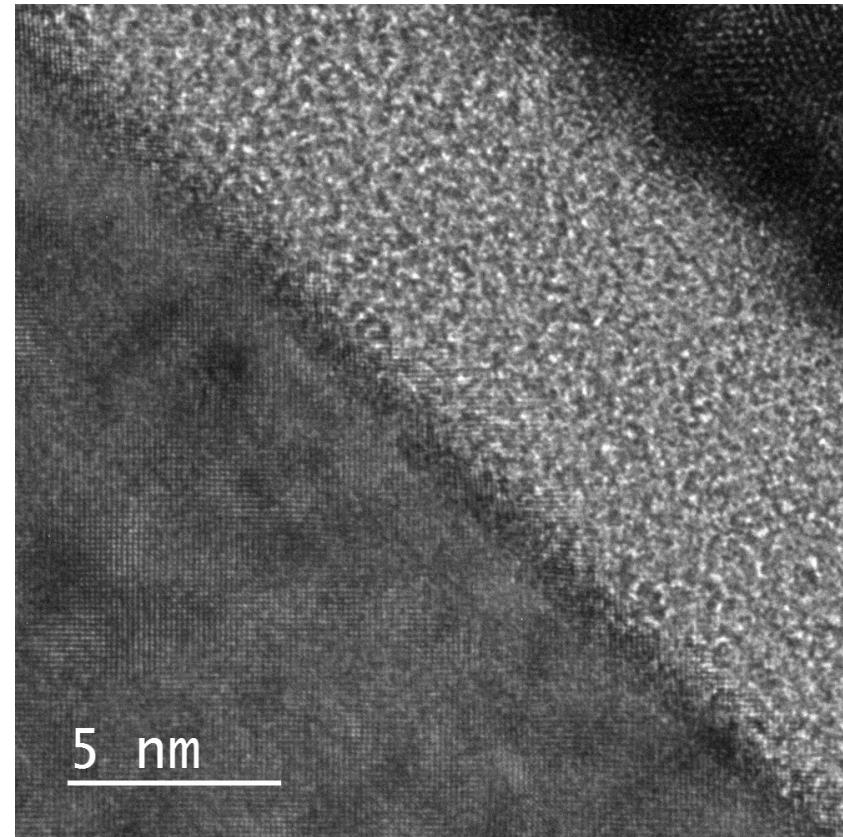
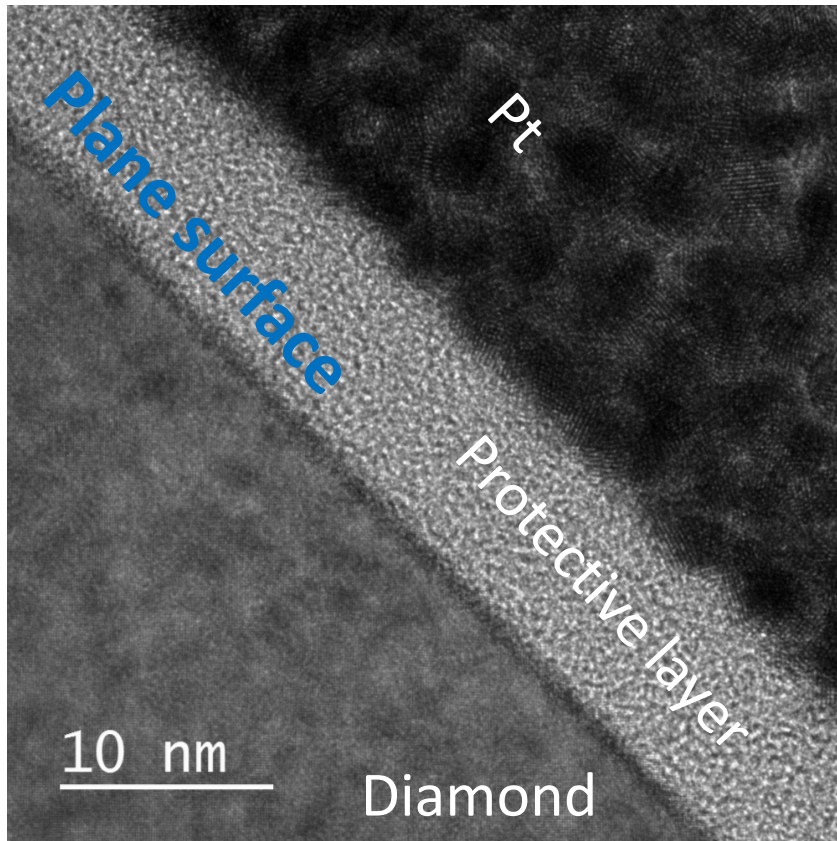
FIB cross sections prepared along:

(100) axis before and after annealing

(110) axis after annealing

As implanted: no amorphization & partially damaged

Cross section along (100) axis

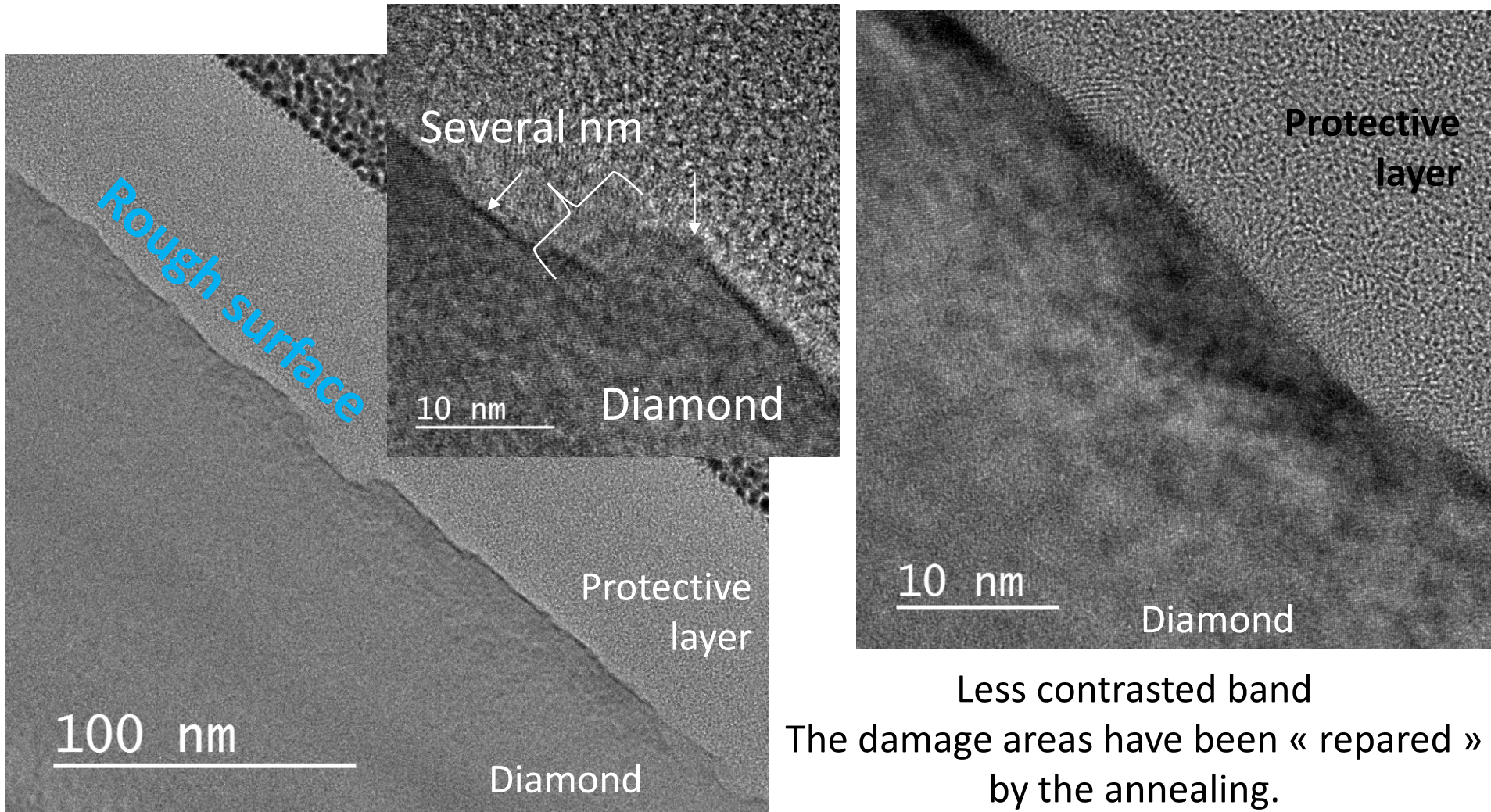


Brigh areas → Crystalline material

Dark areas → Damaged material

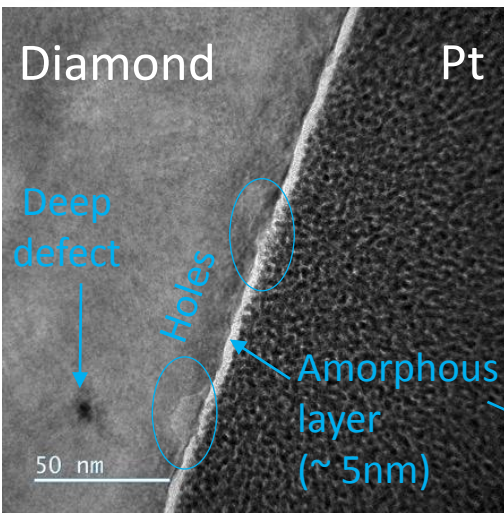
Annealed: damage recovery

Cross section along (100) axis

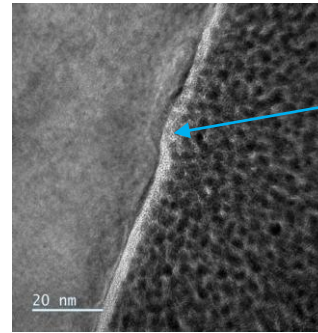


Less contrasted band
The damage areas have been « repaired »
by the annealing.

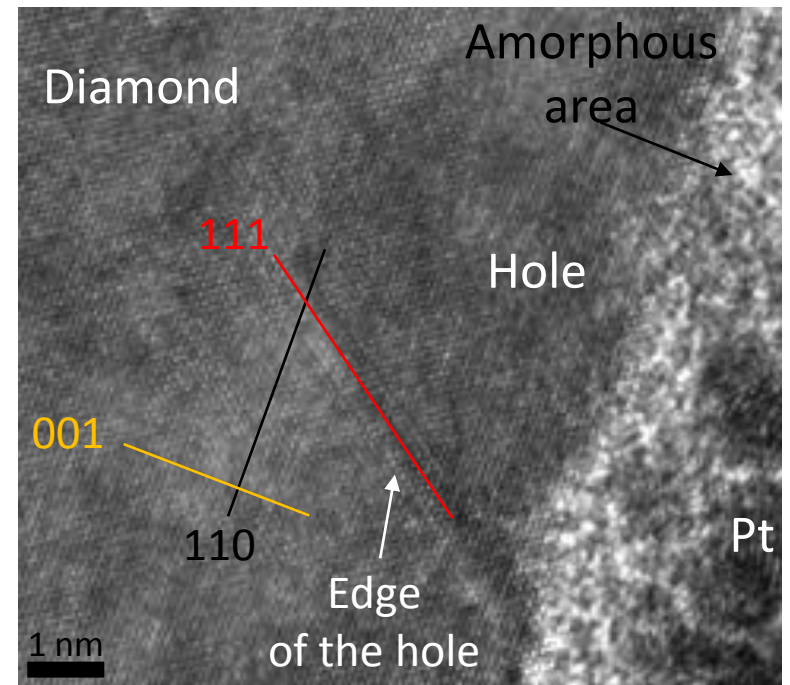
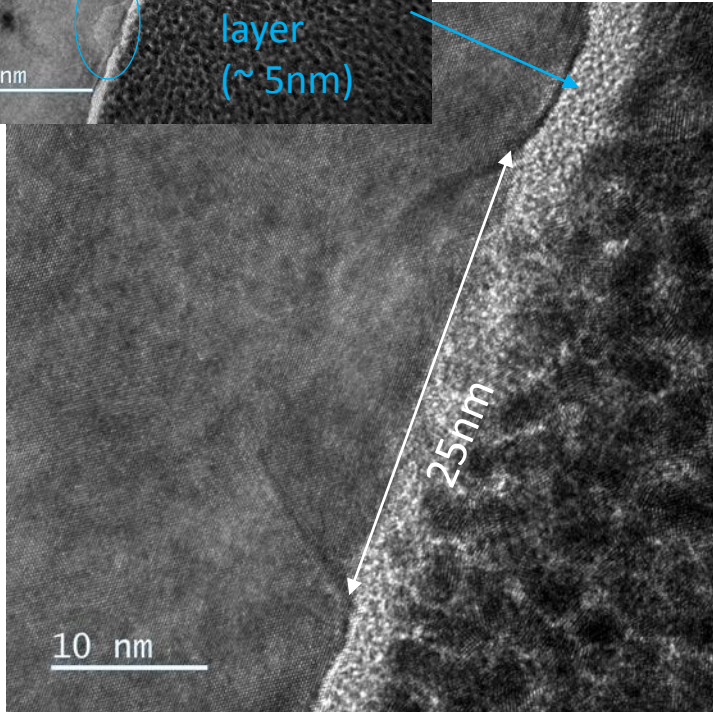
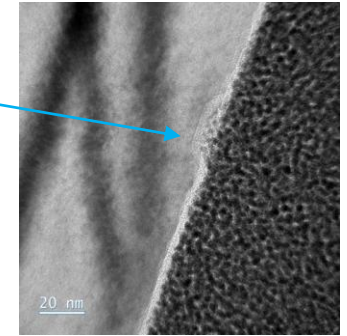
Annealed: holes on the surface



Cross section along (110) axis



Pt from FIB cutting fills the holes.



The implanted zone is:

➤ **before annealing:**

~200 nm, a bit damaged without amorphization

➤ **after annealing:**

**~185 nm, perfectly crystallized with rough surface
and $6.6 \times 10^{19} \leq [B] \text{ (at/cm}^3\text{)} \leq 1.2 \times 10^{20}$.**

Electrical results

Implanted zone: P⁺-type ?

185 nm; [B] ~ 10²⁰ at/cm³

P-type boron-doped layer

10 μm

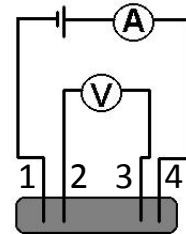
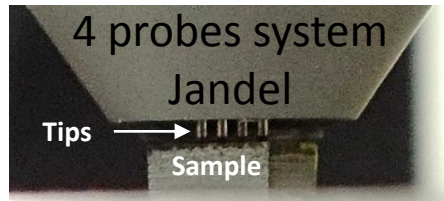
[B] = 8x10¹⁸ at/cm³

Insulating

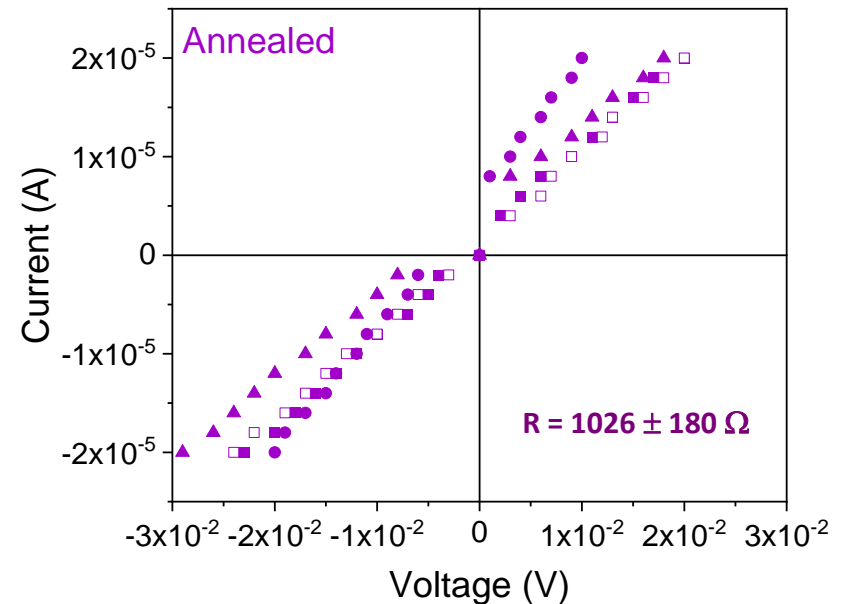
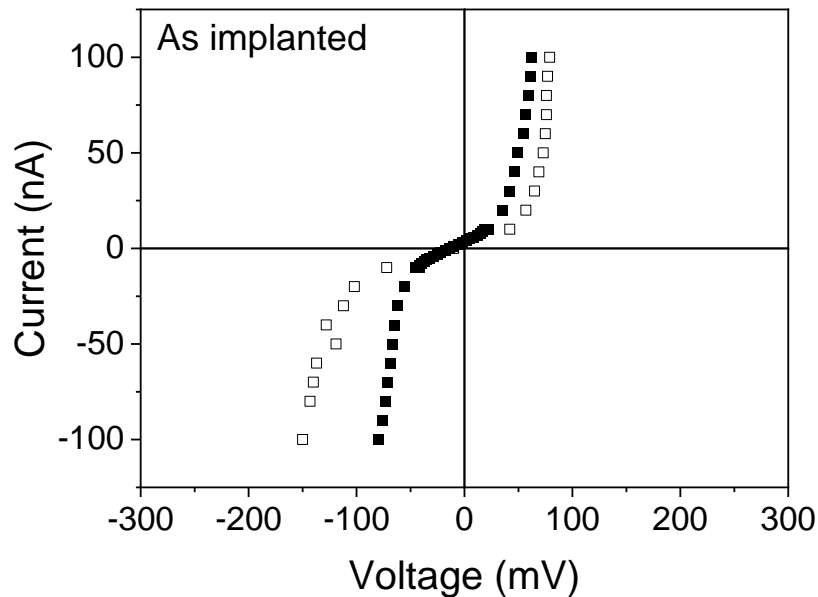
(100) HPHT diamond

substrate

Annealed: conductive layer



Current injection between 1 & 4
Voltage measurement between 2 & 3
I(V) measurement on each diagonal



Resistivity of 0.071 Ω .cm

Current is coming from the implanted zone

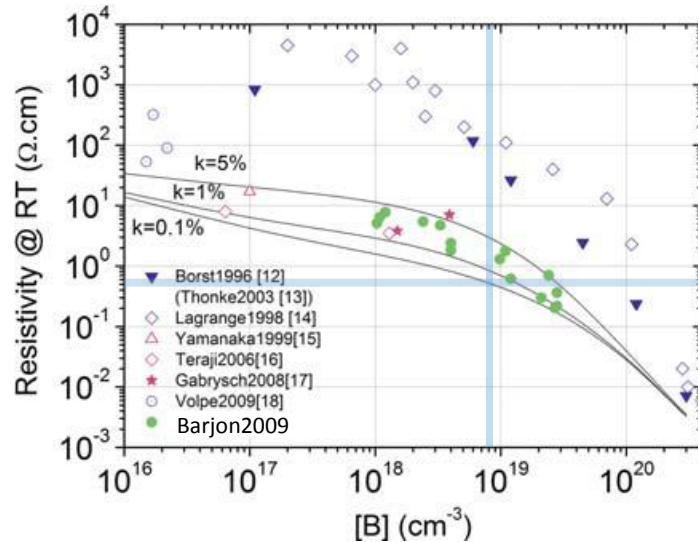
>> 0.071 $\Omega \cdot \text{cm}$ (4 probes)

Expected values from the boron-doped layer



Resistivity

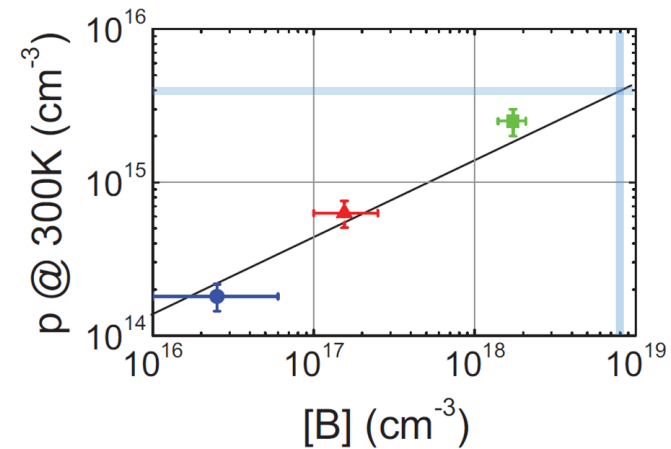
$\geq 0.5 \Omega \cdot \text{cm}$



Barjon et al. *Phys. Status Solidi RRL* **3**, No. 6, 202–204 (2009)

Carrier concentration

$\sim 4 \times 10^{15} \text{ at/cm}^3$



Barjon et al. *PSSa* **209**, No. 9, 1750–1753 (2012)

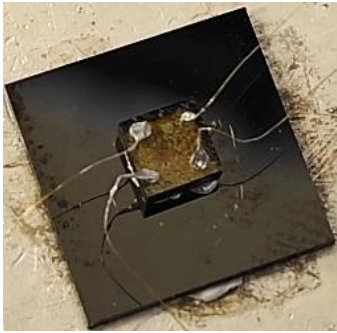
Annealed: ~ 50% of activated boron atoms

Hall measurement at 300K

P-type conductivity

Carrier content, $N_a = 4.4 \times 10^{19} \text{ cm}^{-3}$
 $\gg 4 \times 10^{15} \text{ at/cm}^3$

Resistivity = $0.016 \text{ } \Omega \cdot \text{cm}$ & Mobility = $9.08 \text{ cm}^2/\text{V}\cdot\text{s}$

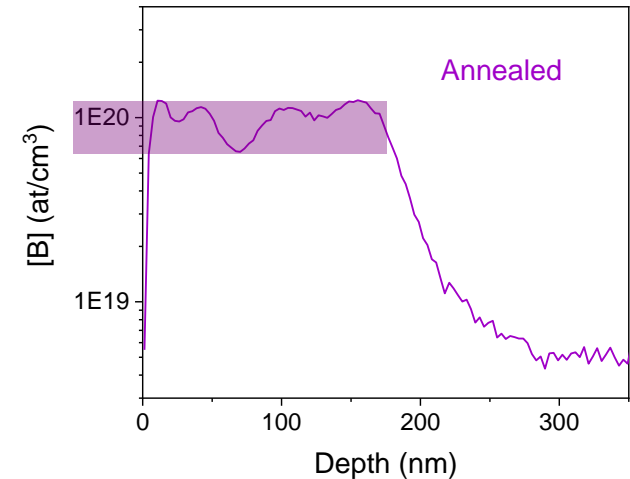


Boron doped layer
10 μm ;
 $[\text{B}] = 8 \times 10^{18} \text{ at/cm}^3$
(100) HPHT Ib
diamond substrate

In the implanted zone
 $6.6 \times 10^{19} \leq [\text{B}] \text{ (at/cm}^3) \leq 1.2 \times 10^{20}$

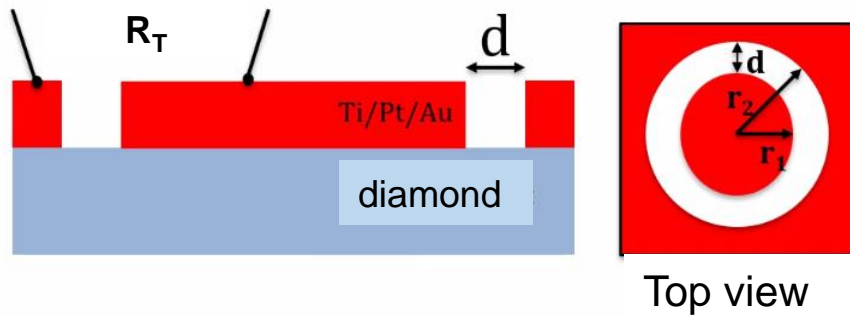


Doping efficiency ($N_a/[\text{B}]$):
 $35\% \leq \eta \leq 67\%$



c-TLM measurements: resistance measurements

c-TLM measurements structure



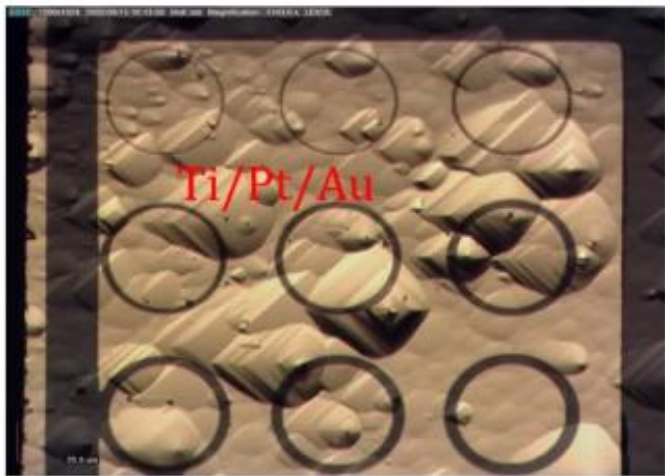
$$R_T = \frac{R_S}{2\pi} \left[L_T \left(\frac{1}{r_1} + \frac{1}{r_2} \right) + \ln\left(\frac{r_2}{r_1}\right) \right]$$

Total resistance

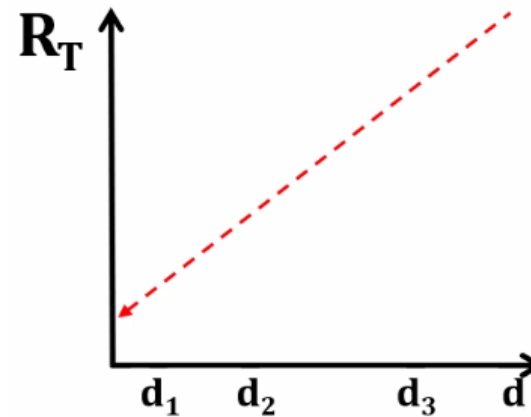
Sheet
resistance

Transfer
length

Contact
dimensions



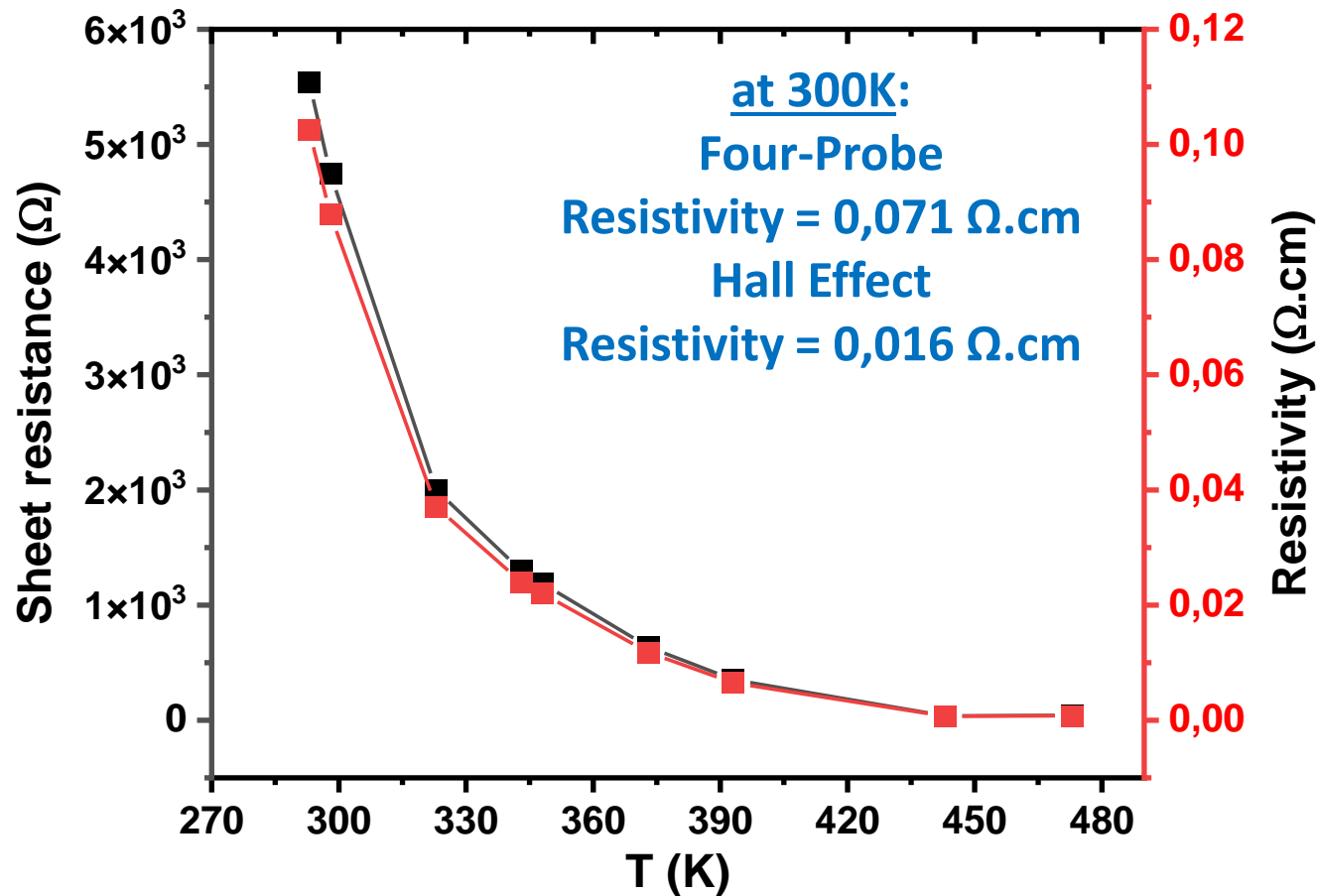
Ti/Pt/Au
50 nm/50 nm/500 nm



$$\rho_C = R_S L_T^2$$

c-TLM measurements: temperature dependence sheet resistance

Resistance measurements in agreement with Hall effect and
four-probe measurements



After annealing, the implanted zone is, at 300K:

- **Conductive**
- **With ~ 50% of active boron**
- **P⁺-type**

c-TLM measurements show a decreasing layer resistivity with temperature and $\rho < 0,08 \Omega.\text{cm}$ at 300K

Conclusions

Ion-implantation conditions incorporated boron in diamond in the range of 10^{20} at/cm³ over ~200 nm without amorphization.

Annealing conditions allowed perfect diamond recrystallization & slightly reduced implanted zone.

The implanted layer presents P-type conductivity with 4×10^{19} cm⁻³ activated boron acceptors at 300K, and room temperature c-TLM measurements of resistivity (< 0.08 Ω .cm) corroborate Hall Effect and Four-Probe results (0.016 and 0.071 Ω .cm respectively)



200
 μ m

Perspectives

- Hall Effect measurements as a function of temperature
- Protect the surface to avoid etching during annealing
- Use n-type phosphorus-doped layer for boron implantation
- Increase boron-doping efficiency

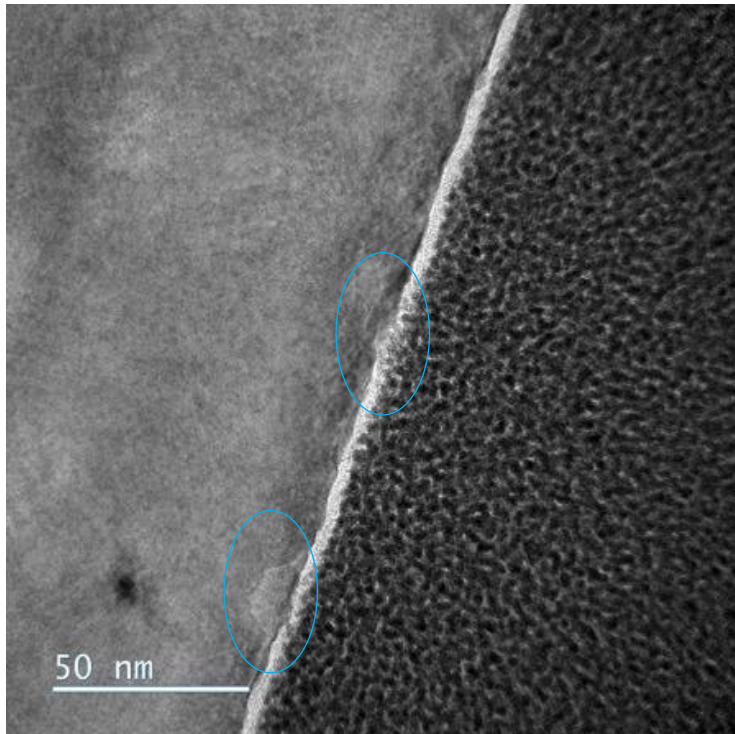
Thank you for your attention



Annealed: holes on the surface

TEM

Holes of $\Phi \sim 25$ nm
are not entirely
covering the surface



AFM

Many holes
of the same dimension
than observed by TEM

