A topic of around diamond detectors

Special topic 59 02/15/2019

Introduction - Motivation

Diamond as a Sensor Material:

Distinct properties interesting for HEP applications:

- Large band gap → low leakage current
- High thermal conductivity → no cooling required
- Low leakage current → low noise
- Low dielectric constant → low capacitance, low noise
- Large displacement energy → high radiation tolerance

Disadvantages:

- Large band gap → planar detectors give ~1/2 signal of Si (of same t)

At large radiation doses, without gain, it is the drift distance relative to the mean free path that determines the size of the signal

- Next Talk (Nicola Venturi) → mean free path

-- Borrow this page which explains well --

Properties

Quantity	Diamond	Si	Ge	GaAs
Atomic number Z	6	14	32	31, 33
Number of atoms N [10^{22} cm^{-3}]	17.7	4.96	4.41	4.43
Mass density ρ [g cm^{-3}]	3.51	2.33	5.33	5.32
Radiation length X_0 [cm]	12.0	9.4	2.3	2.3
Relative dielectric constant ϵ	5.7	11.9	16.3	13.1
Band gap E_g [eV]	5.47	1.12	0.67	1.42
Intrinsic carrier density n_i [cm^{-3}]	$< 10^3$	1.45×10^{10}	2.4×10^{13}	1.79×10^6
Resistivity ρ_c [Ω cm]	$> 10^{12}$	2.3×10^5	47	10^8
Electron mobility μ_e [cm^2 V^{-1} s^{-1}]	1800	1350	3900	8500
Hole mobility μ_h [cm^2 V^{-1} s^{-1}]	1200	480	1900	400
Saturation field E_s [V cm^{-1}]	2×10^4	2×10^4	2000	3000
Electron saturation velocity v_s [10^6 cm s^{-1}]	22	8.2	5.9	8.0
Operational field E_o [V cm^{-1}]	10^4	2000	1000	2000
Electron operational velocity v_o [10^6 cm s^{-1}]	20	3	3	10
Energy to create e-h pair E_{eh} [eV]	13	3.6	3.0 (@77 K)	4.3
Mean MIP ionization q_p [e μm^{-1}]	36	108	340	130

Far less noise fluctuation,
can work without PN junction == without depletion

Classification of diamond type

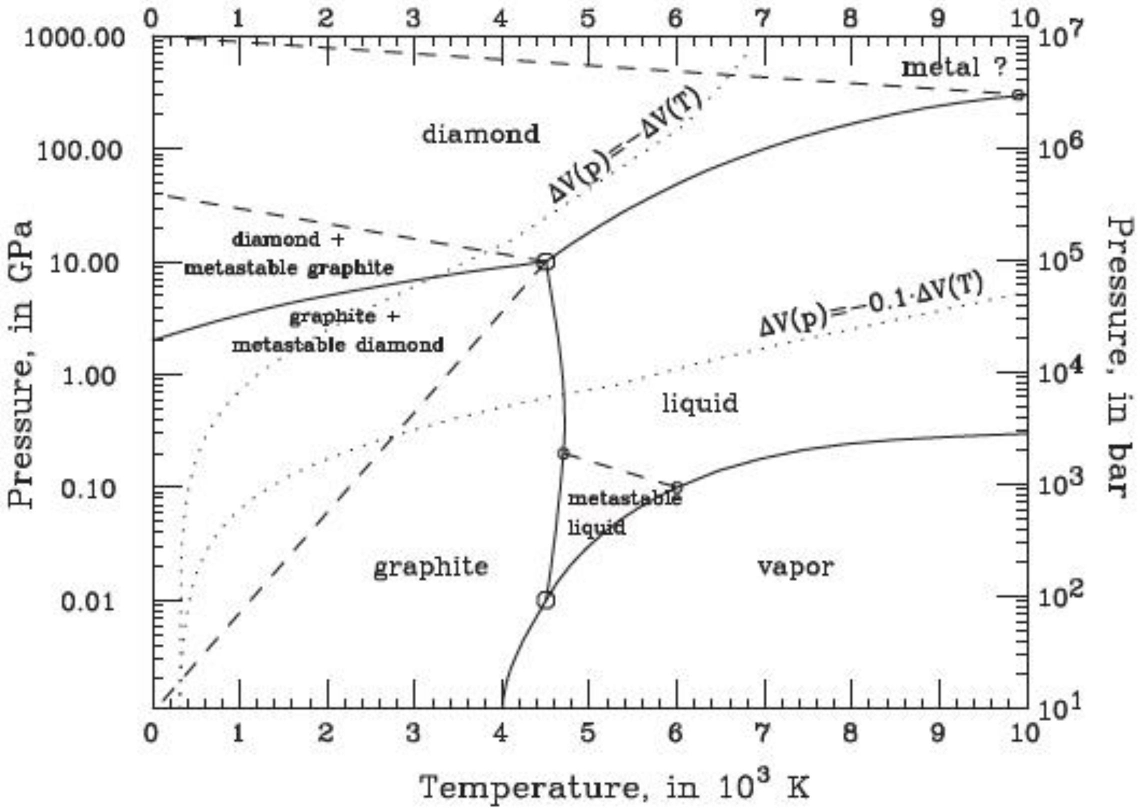
Type	Impurities	Comments
Ia	Aggregated nitrogen up to 2500 ppm	Most natural diamonds
Ib	Substitutional nitrogen up to 300 ppm	Most synthetic diamonds
IIa	Substitutional nitrogen < 1 ppm	Detector material
IIb	Boron doped	p-type semiconductor

Because of impurity (nitrogen) which acts as “trap”, it can not be used as this kind of detector

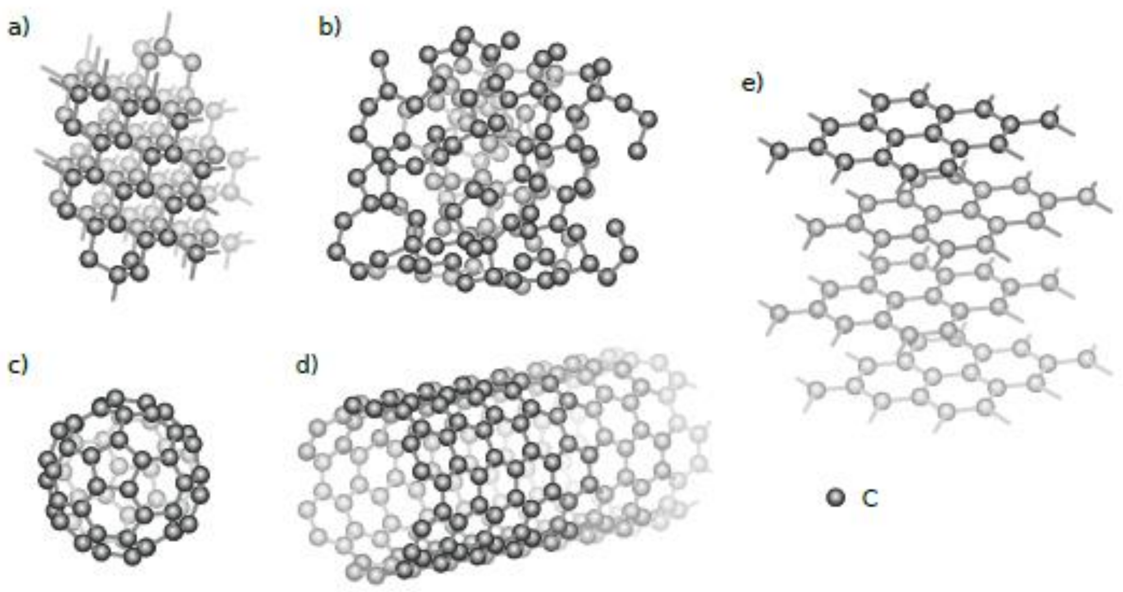
High pressure & High temperature

CVD method

Reference

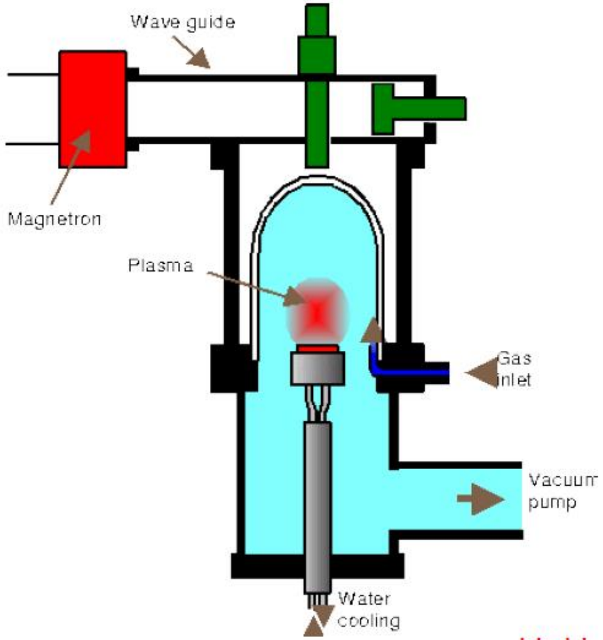


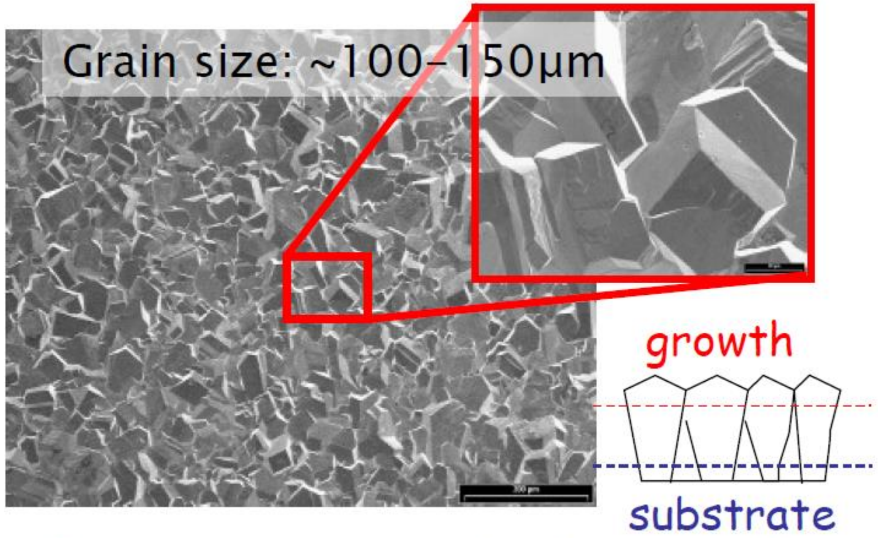
(a)



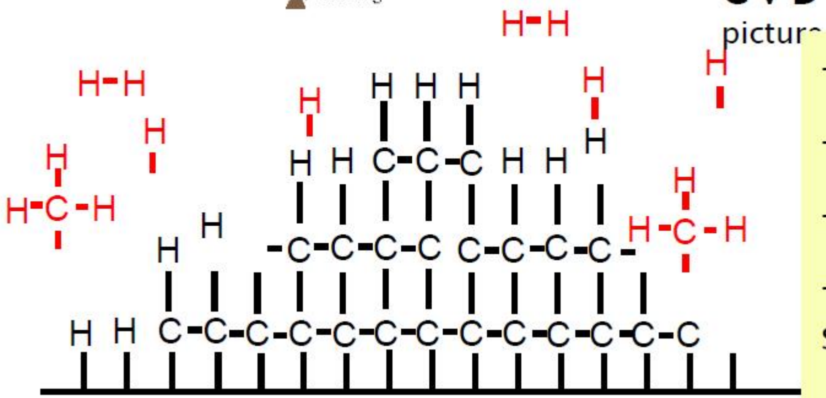
(b)

CVD Diamond Production





columnar structure of **polycrystalline CVD diamond** (SEM picture M.Bruzzi)



- Columnar growth of diamond crystal
- Si or diamond substrate
- Growth speed ~ few µm/hour
- Grains grow wider from substrate side
- recently: **single crystal diamond**

Key Point : Progress on making(growing) larger size <-- within this 10 years

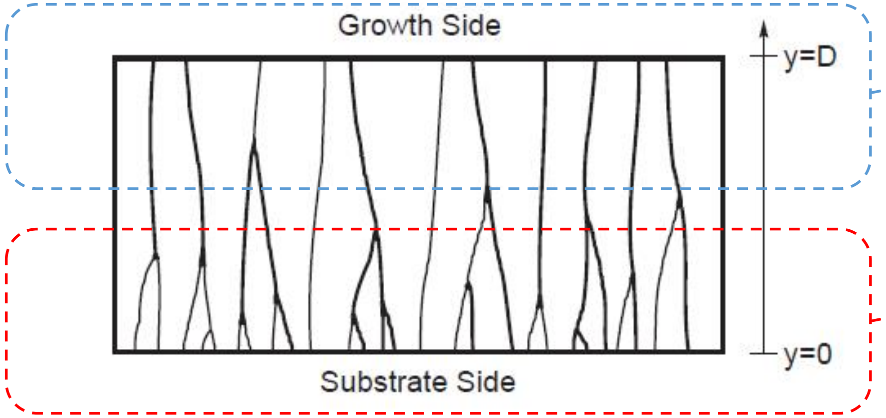
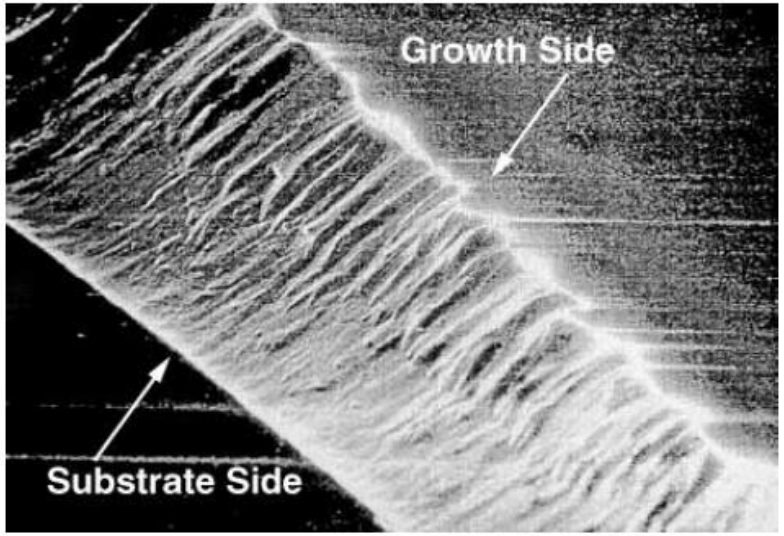


Figure 3.3: Schematic section of a diamond film.

Cut the bottom and only use the upper part for detector

Density of boundaries are high at the substrate side.



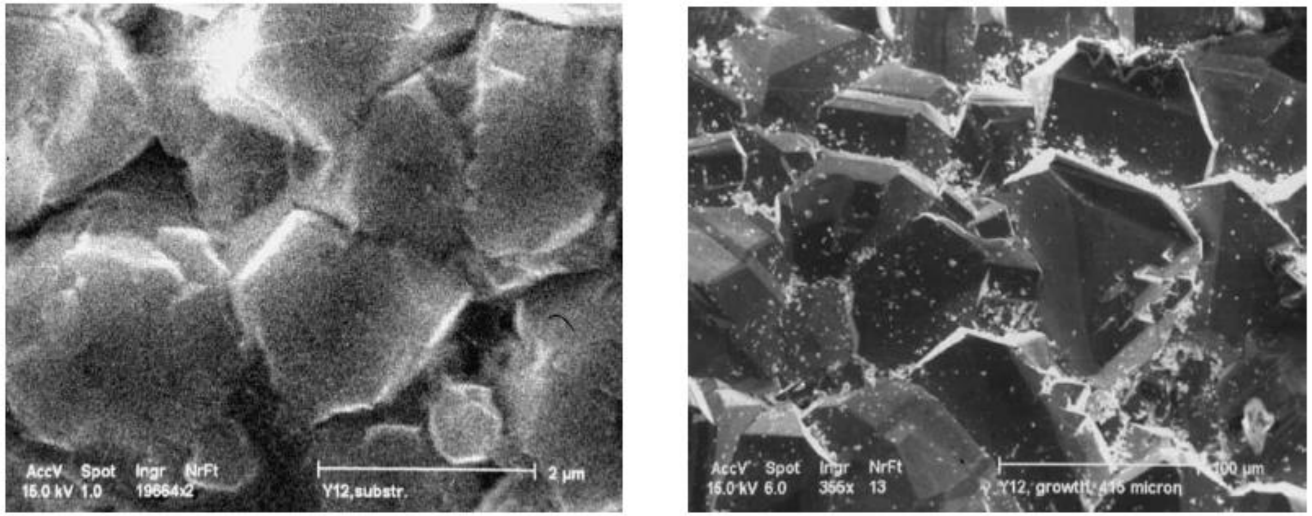


Figure 3.5: Left: Substrate (left) and growth (right) sides of the same diamond sample (415 μm thick). Note the different scales of the images: 2 μm for the substrate side and 100 μm for the growth side.

Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC, HL-LHC and Beyond

RD42

The RD42 Collaboration [1] **from** CERN-LHCC-2018-015 / LHCC-SR-005 27/05/2018

Example： Beam Condition Monitor

The ATLAS Diamond Beam Monitor

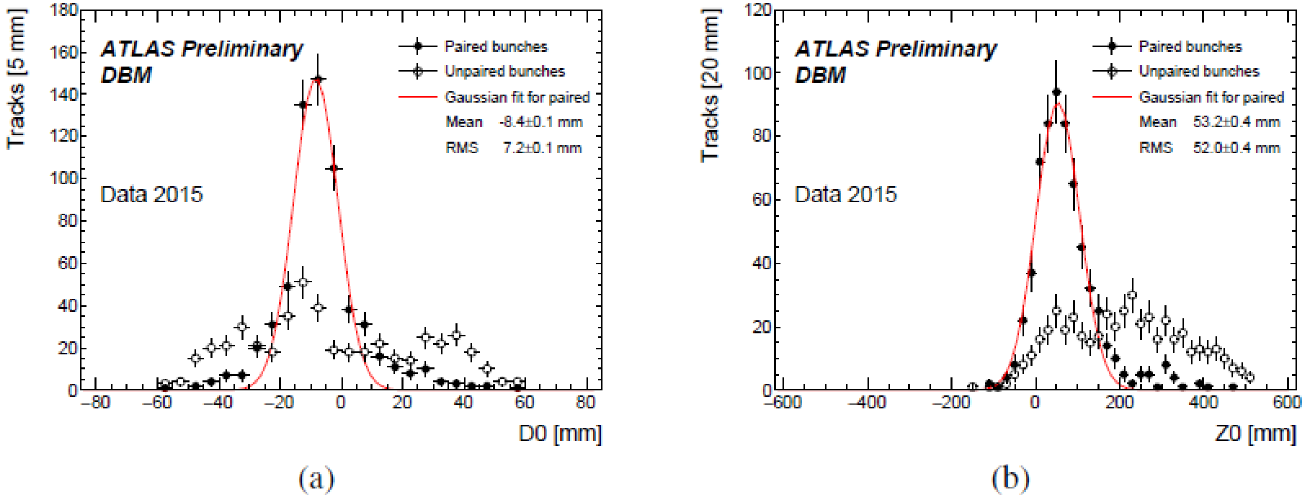
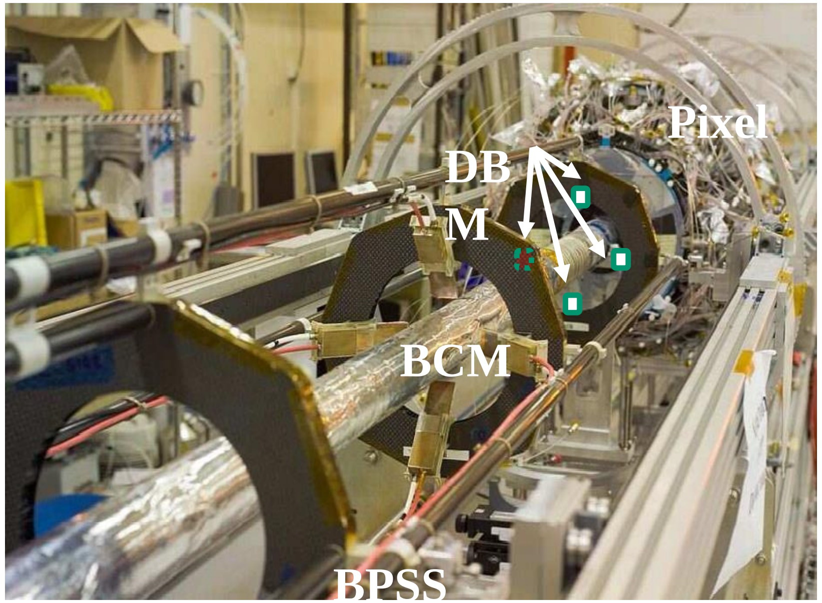
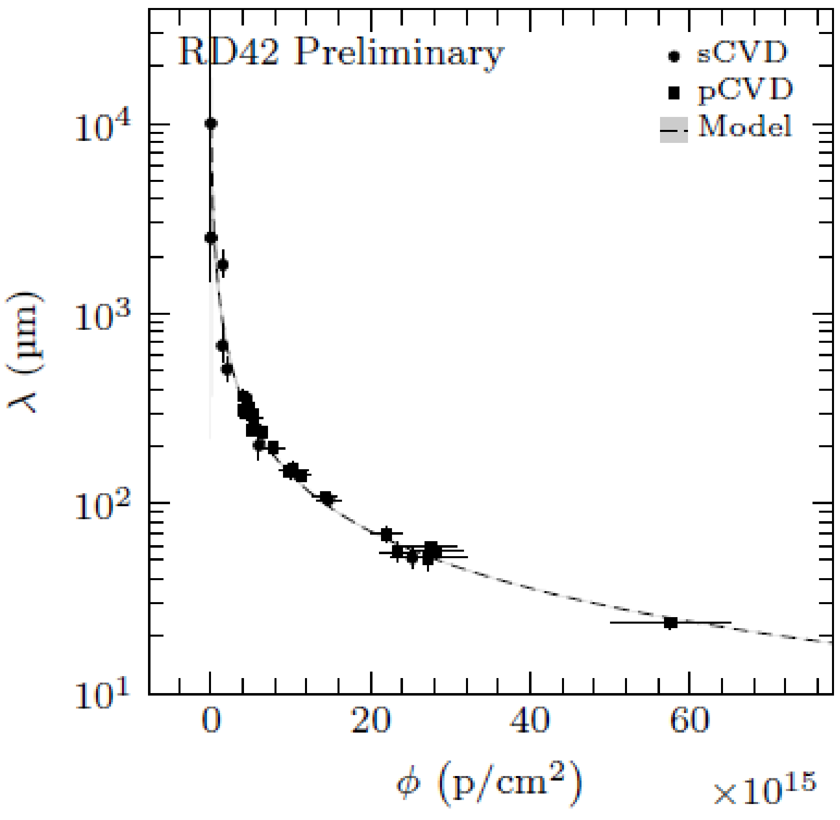


Figure 4: (a) Radial distance and (b) longitudinal distance of of the projected particle tracks closest approach to the interaction point recorded by a single DBM telescope with preliminary alignment.

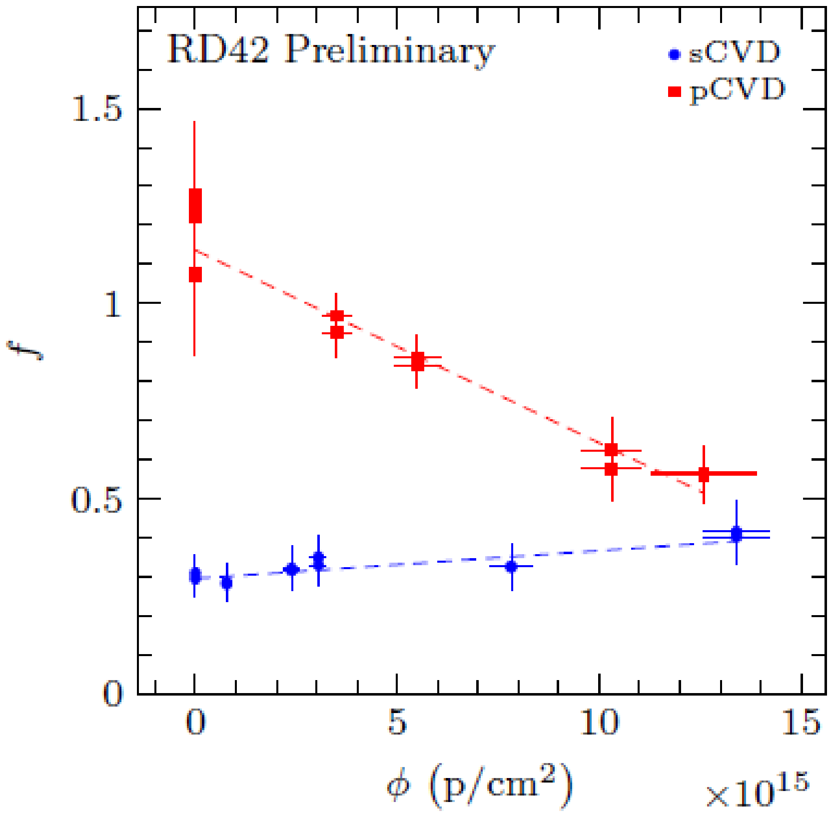


Radiation Tolerance

CERN-LHCC-2018-015 / LHCC-SR-005
27/05/2018



(a)

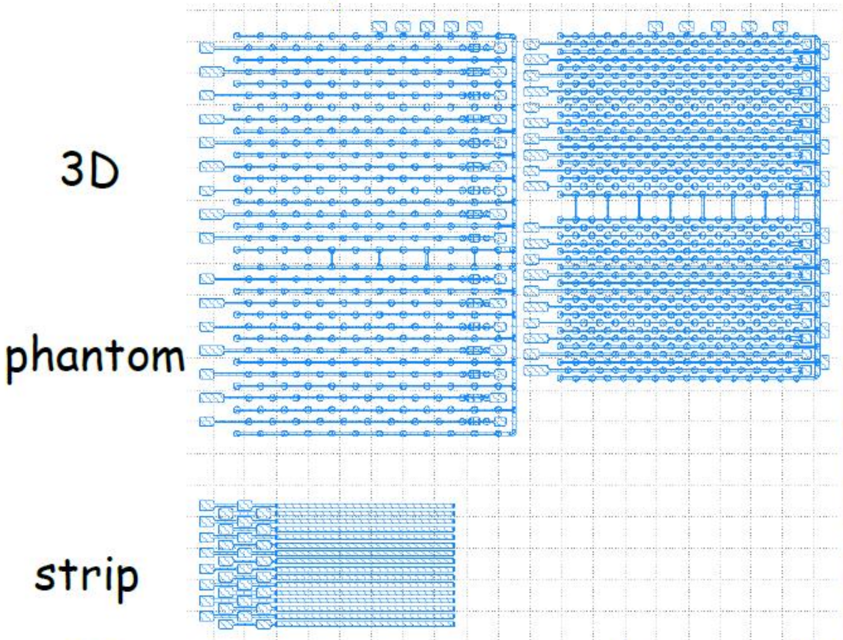


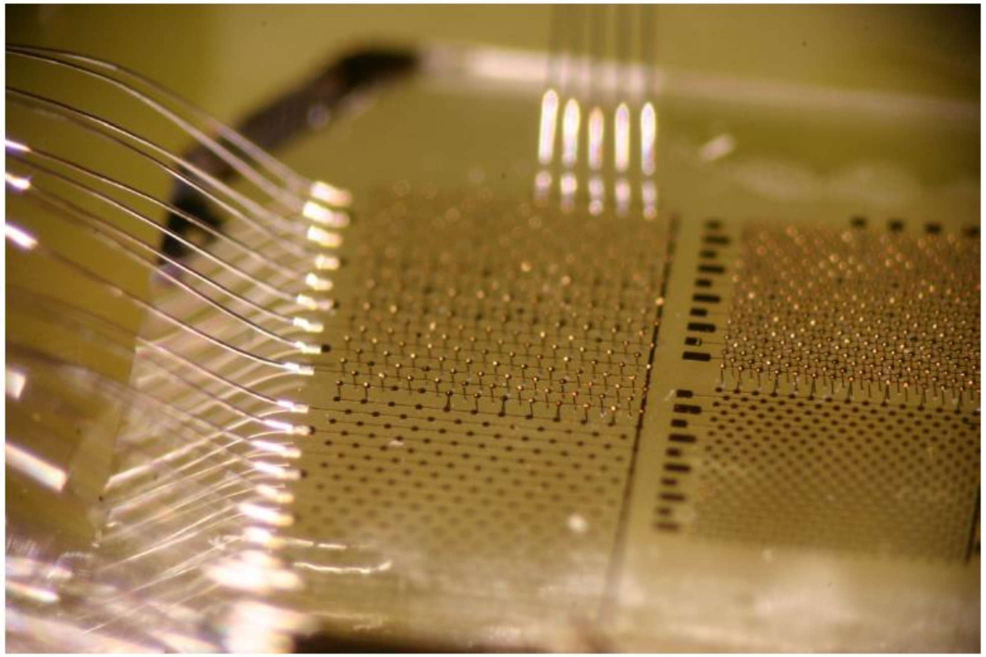
(b)

Figure 3: (a) Measured MFP (λ) as a function of 24 GeV proton fluence compared to the radiation damage model (dotted curve) [15]. (b) Signal response figure of merit f for pCVD and scCVD samples as a function of 800 MeV proton fluence along with linear fits to pCVD (red line) and scCVD (blue line) data [15].

3D Sensor Development

Simultaneously readout all 3 devices





Two years ago we showed the results in scCVD diamond

- -Compared scCVD strip detector (500V) with 3D (25V)

Last year the first 3D device in pCVD diamond

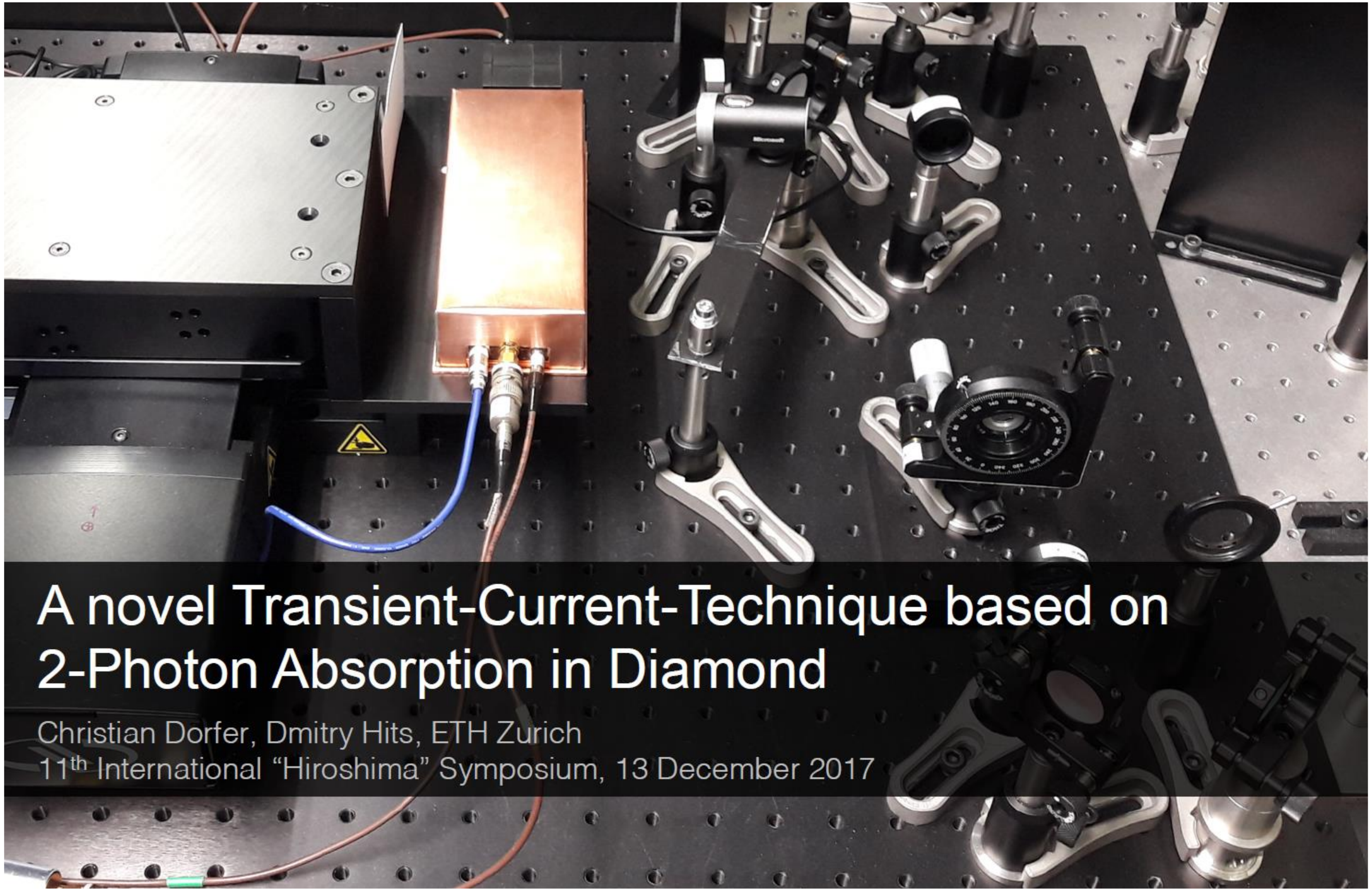
- -Compare pCVD strip detector (500V) with 3D (60V)

This year the first 3D pixel detector in pCVD diamond

HSTD11 – Okinawa, Japan Harris Kagan 13

… we can see many characterization results from above slide or others

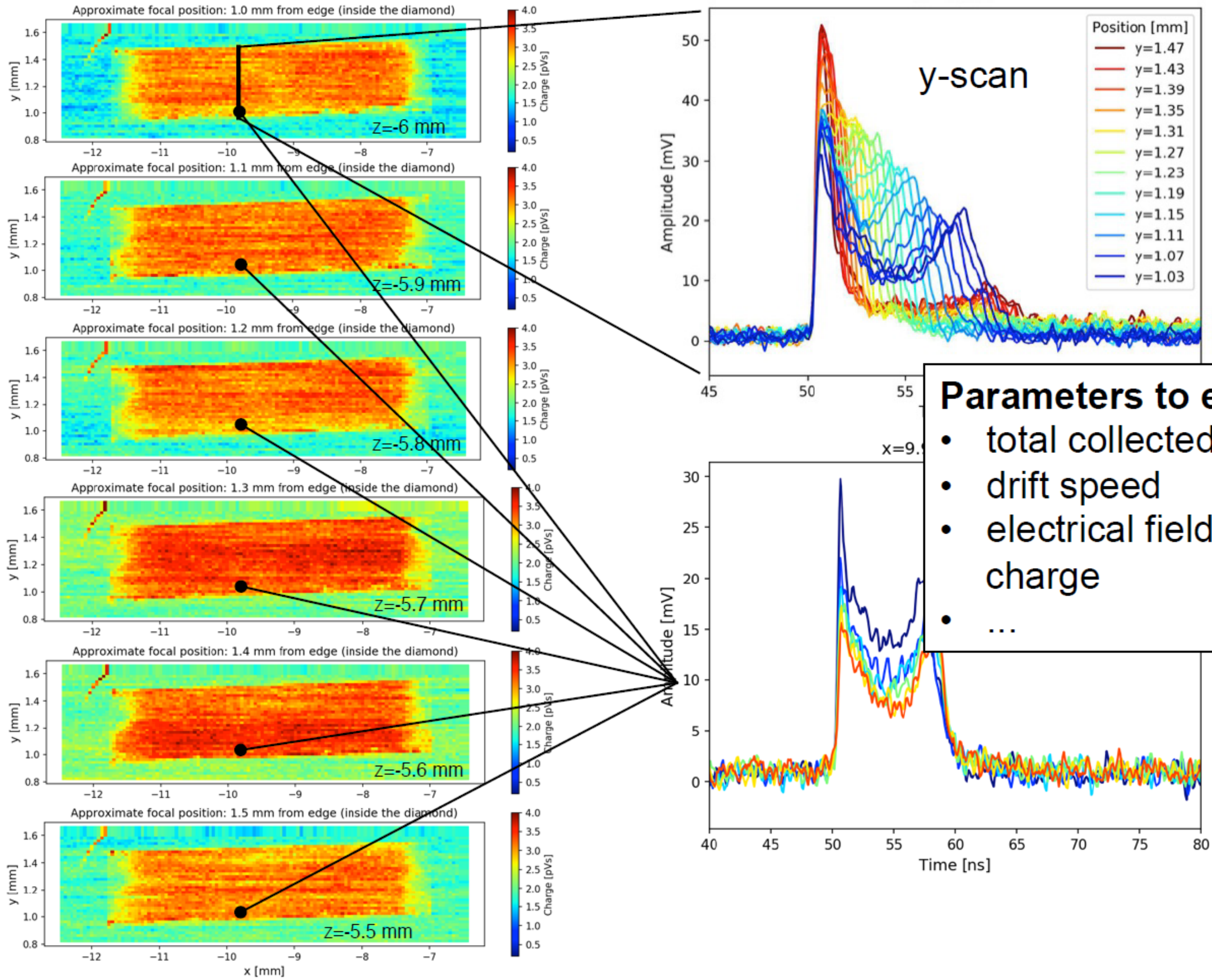
Other example of characterization : two-photon TCT on diamond detector



TCT scan results

First 3D Scan

Bias voltage -400V (0.7V/um), 50 waveform averaging, 3993 scan points, 0.2 nJ pulse energy



Parameters to extract:

- total collected charge
- drift speed
- electrical field → space charge
- …

PN-junction

Producing “N-type” is/was very difficult (I do not follow why it is) , gradually it becomes possible but still challenging

P-type

N-type

	Conventional (1 0 0)	(1 1 0)	(1 1 1)	(1 1 3)
Substrate availability	++	+	−	−−
Window of suitable growth conditions	+	+	−	++
Growth rates	−	++(×5)	−−	+(×2)
Crystalline quality	++	+	−	++
Boron doping efficiency	−	+	++(×10)	+(×5)
Nitrogen doping efficiency	−	?	++	+
NV center preferential orientation	−−(0%)	−(50%)	++(100%)	+(73%)

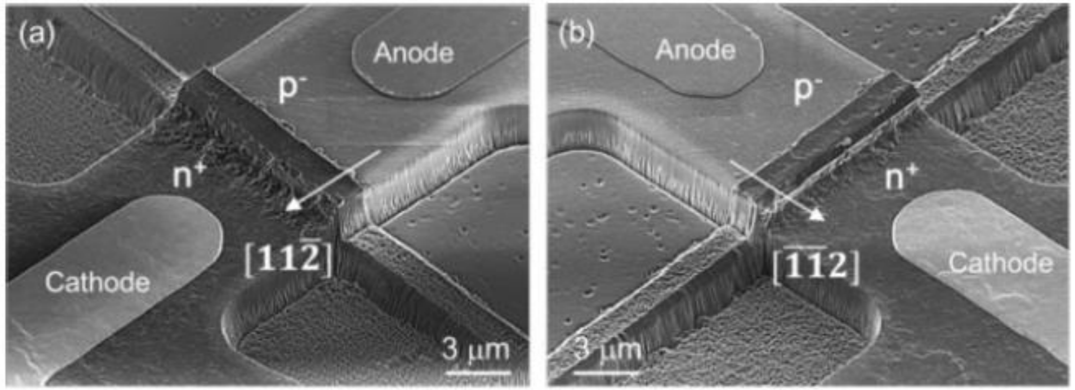
For each criterion considered, ++ indicates a high suitability while −− indicates that the orientation is not favorable. *CVD*, chemical vapor deposition; *NV*, nitrogen-vacancy.

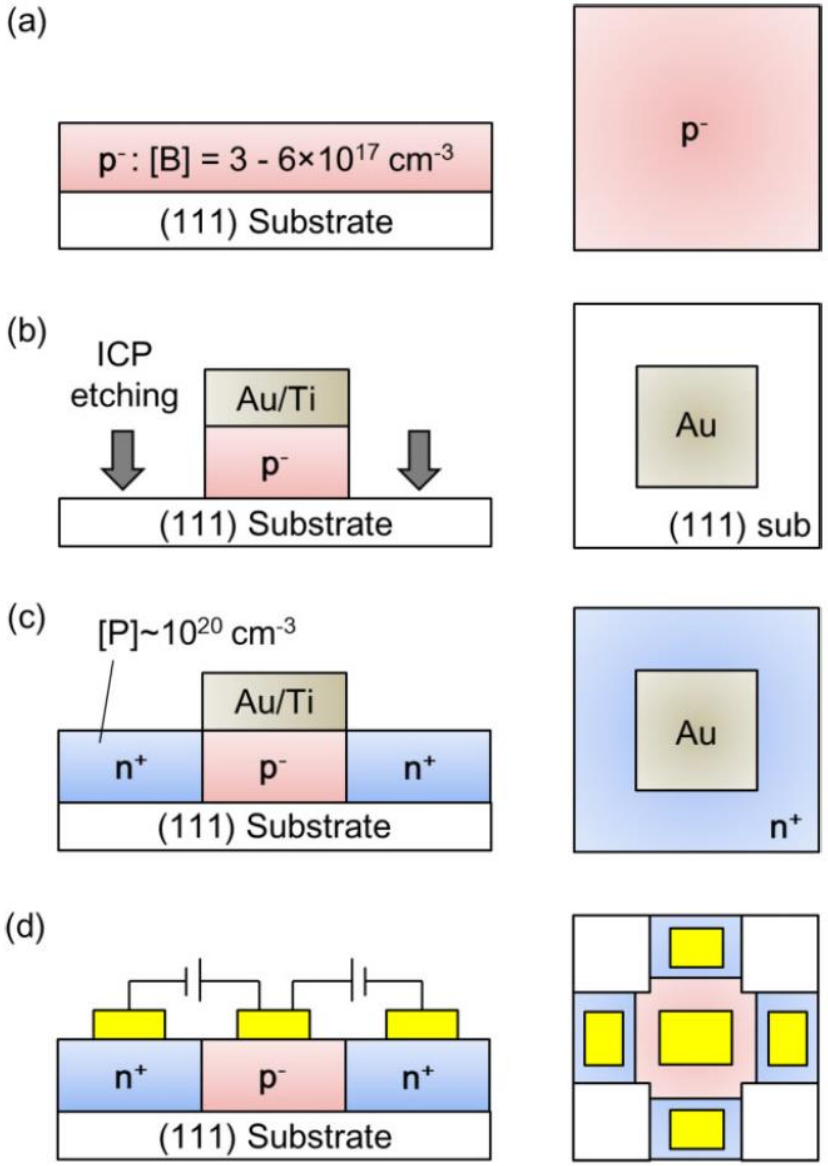
From “Power Electronics Device Applications of Diamond Semiconductors”

Example of PN structure with diamond

Fabrication of diamond lateral p–n junction diodes on (111) substrates

Kazuki Sato[1], Takayuki Iwasaki[1,2,3], Maki Shimizu[1,3], Hiromitsu Kato[3,4], Toshiharu Makino[3,4], Masahiko Ogura[3,4], Daisuke Takeuchi[3,4], Satoshi Yamasaki[3,4], and Mutsuko Hatano[*,1,2,3]





Recall of LGAD structure

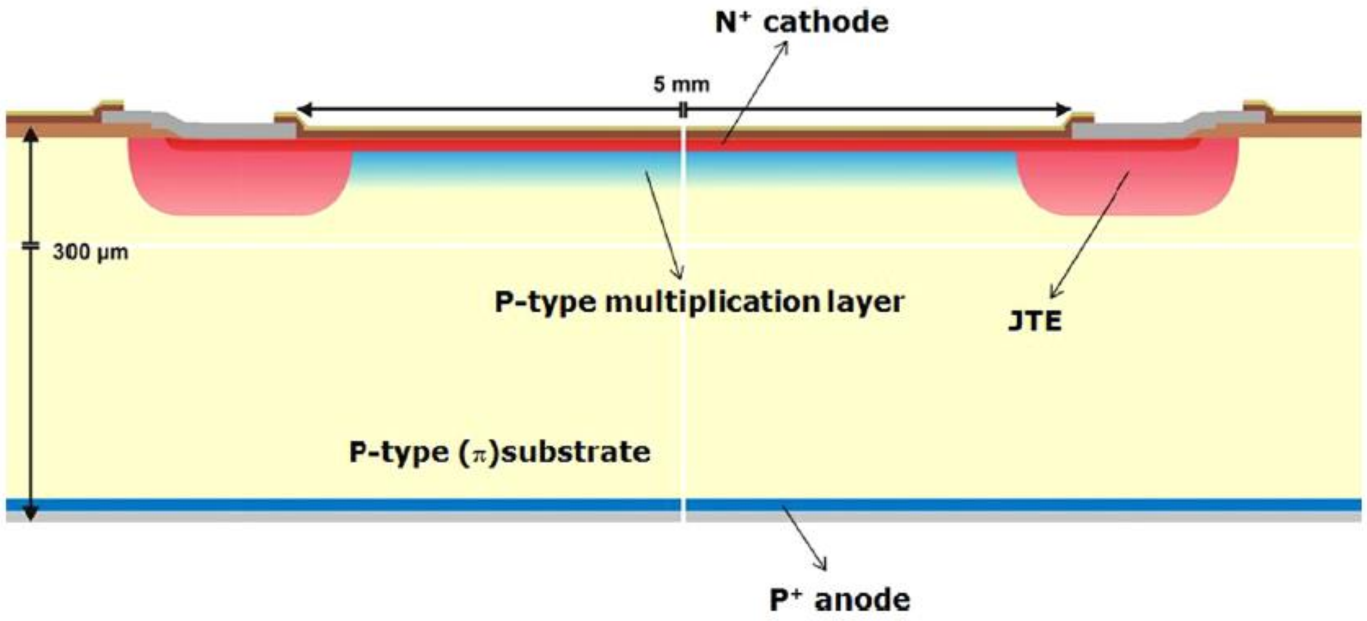


Fig. 4. Schematic cross-section of the LGAD pad design with a JTE structure protecting the junction edge termination.

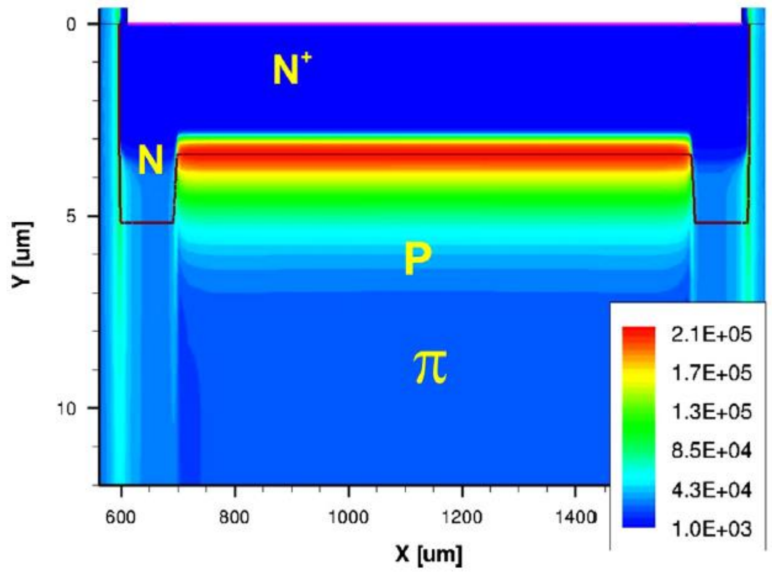


Fig. 5. Simulated electric field distribution throughout the multiplication junction of a LGAD ended with a JTE.

Summary

-- Diamond “detector” is now developed and might be replaced with the current silicon detector where the radiation is high.

-- Main factor for usage of this diamond detector is the progress of CVD process which can make the detector size more than few mm now.

-- Making PN-junction for detector level is not realized yet, and a challenge.

My comment

-- One obvious drawback of this diamond detector is the small signal compared with that of silicon detector

-- If LGAD-like structure is realized on this diamond detector, what happen ?

but I'm also not sure what happen at the "multiplication layer" beyond $10^{16}/cm^2$