IBIC imaging in synthetic single crystal diamond

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- IBIC at the Surrey microbeam
- Introduction to sample geometry
- CCE images – variations in hole sensitive transport due to priming, polarisation and event rate….
- Time resolved signals and detrapping
- Summary/ Conclusions

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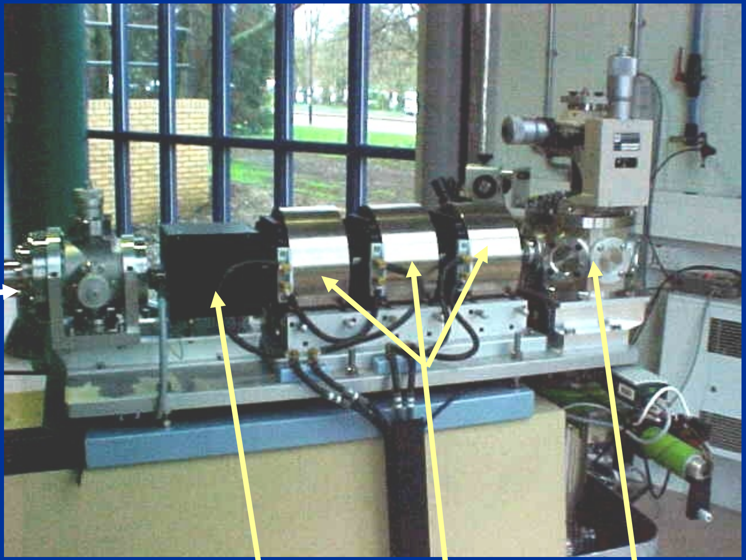
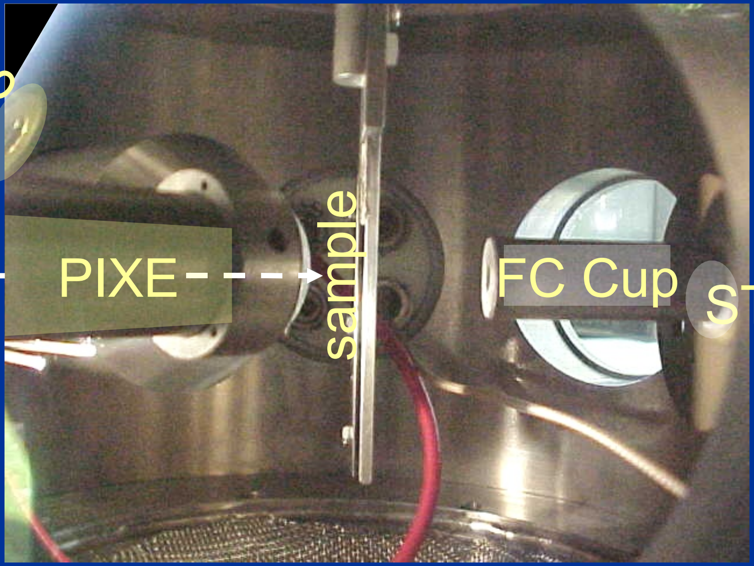
The Surrey microbeam

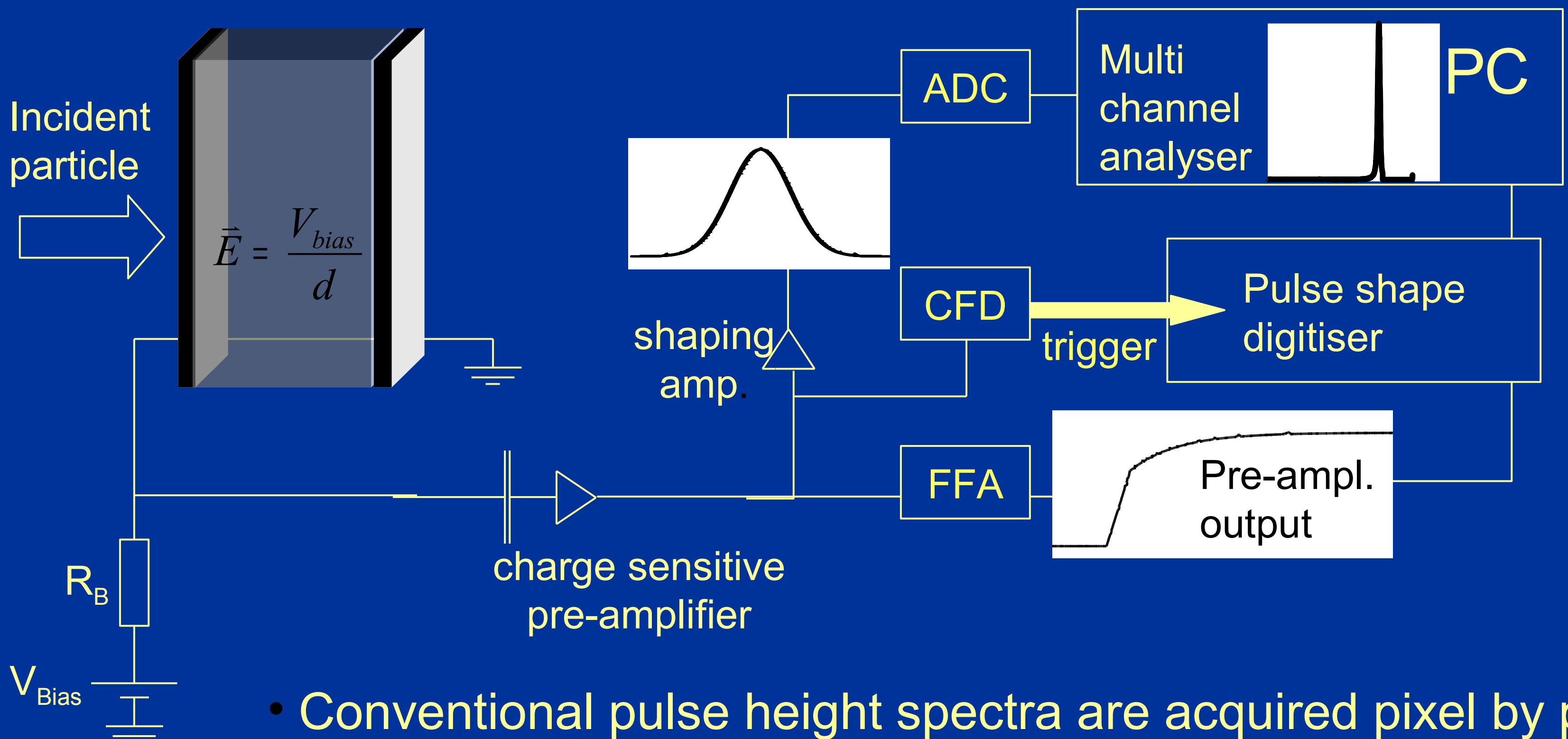
- 2 MV Tandetron
  i.e. up to 3 MeV H^+
  6 MeV He^{2+}
- Beam spot size < 4 μm x 4 μm
- Scan size up to 2.5 mm x 2.5 mm





Variable sample temperature between 100 K and 300 K.

IBIC at the Surrey microbeam



- Conventional pulse height spectra are acquired pixel by pixel on an event by event bases and analysed offline (Omdaq).
- The minimum sampling interval of the digitiser is 2 ns.
- Typically, 200 samples per pulse are acquired (with a few hundred pulses processed per second).
- Typical beam currents are < 0.5 fA (~1000 events/sec), set-up with a Silicon detector (unfortunately not perfectly stable).

Origin of the single crystals

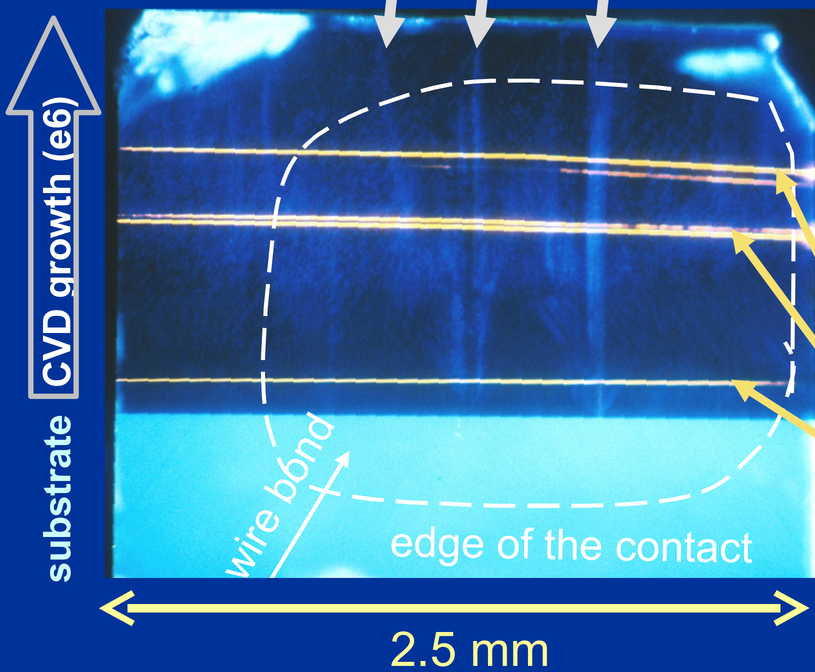
IBIC analysis of 2 samples grown by Element Six using a CVD process based on that described by Isberg et al.:

- D1 - vertically cut sample containing dislocations and Nitrogen doped layers supplied directly by Element Six for comparative analysis

- D2 - High purity detector sample, made available courtesy of John Morse (ESRF)

D1 – vertically cut

Blue band A luminescence,
associated with dislocations



Sample D1:

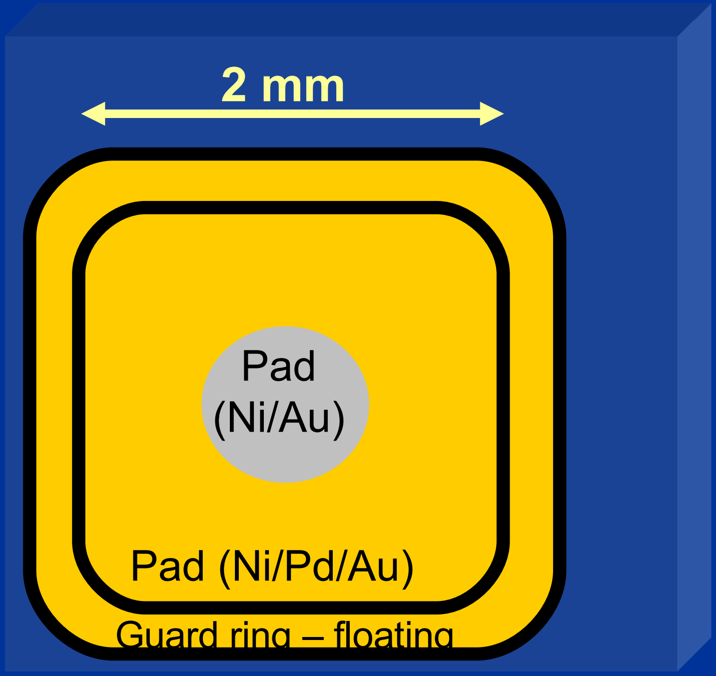
- Thickness = 0.49 mm
- evaporated Ti/Au
  (50 nm/300 nm)
  Contacts annealed at 400 ^{o}C

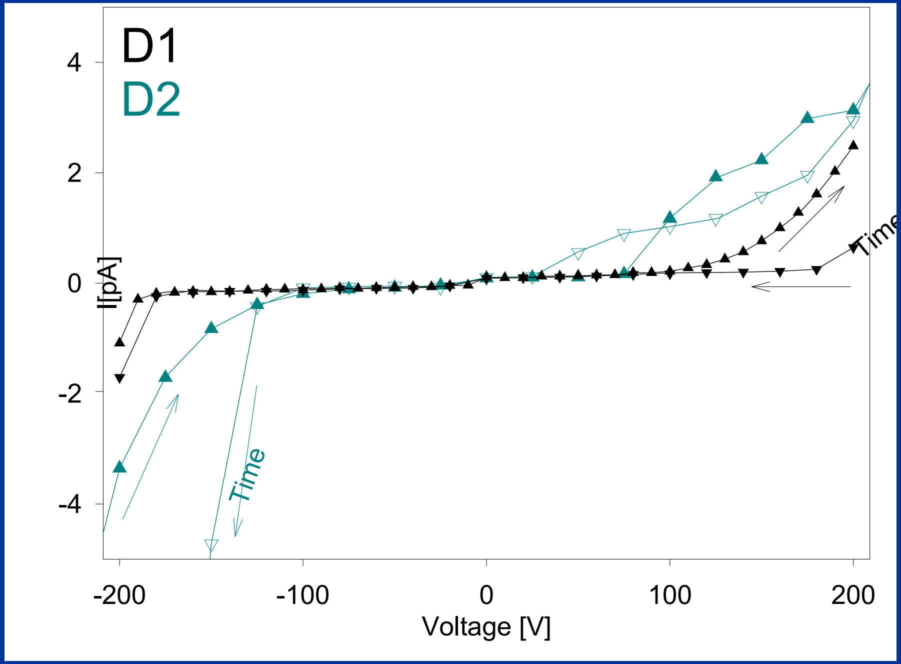
Nitrogen intentionally introduced during the growth process

D2 – asymmetric contacts

Sample D2:

- Thickness = 0.35 mm
- Ni/Pd/Au on the front pad and guard ring – centre hole Ni/Au
- Ti/Pd/Au (annealed) contact on the back





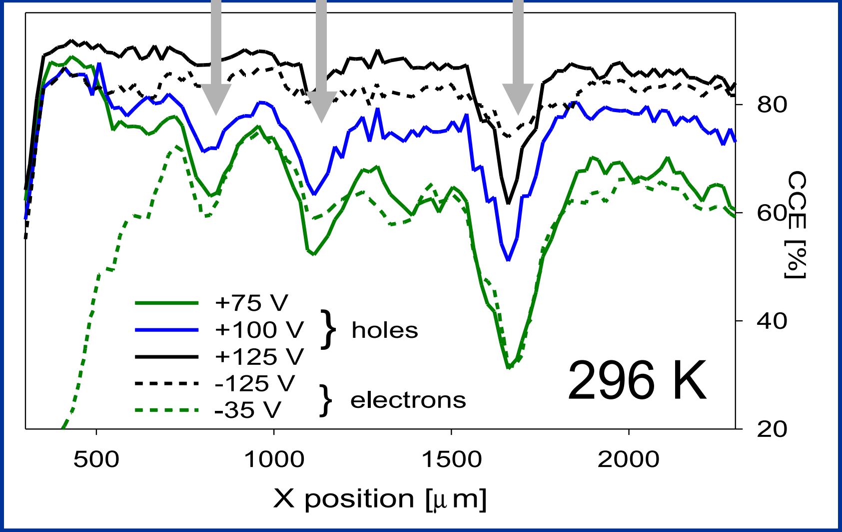
IV is not perfectly symmetric in both cases.

Discrepancy with the scan direction could be due to not fully reached stabilisation.

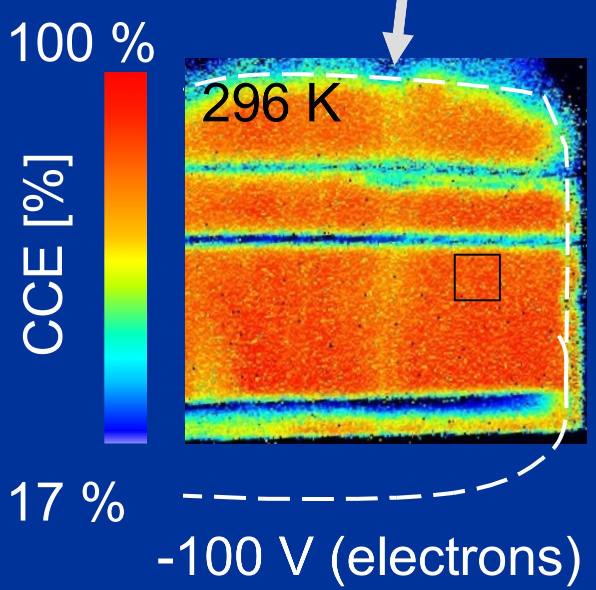
Charge collection efficiency (CCE)in D1

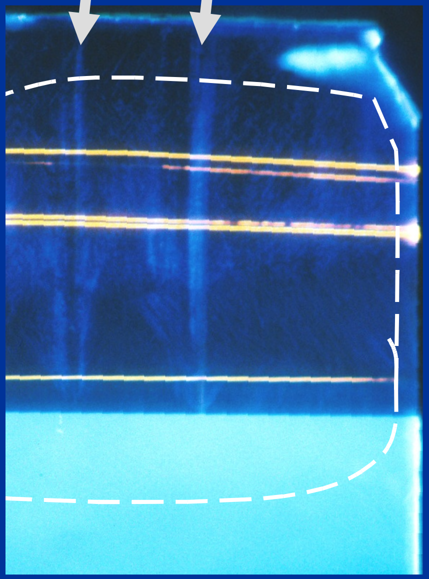
<u>Sample D1:</u>

IBIC with 2.6 MeV protons
(range 35 µm)



Blue band A luminescence,
associated with dislocations



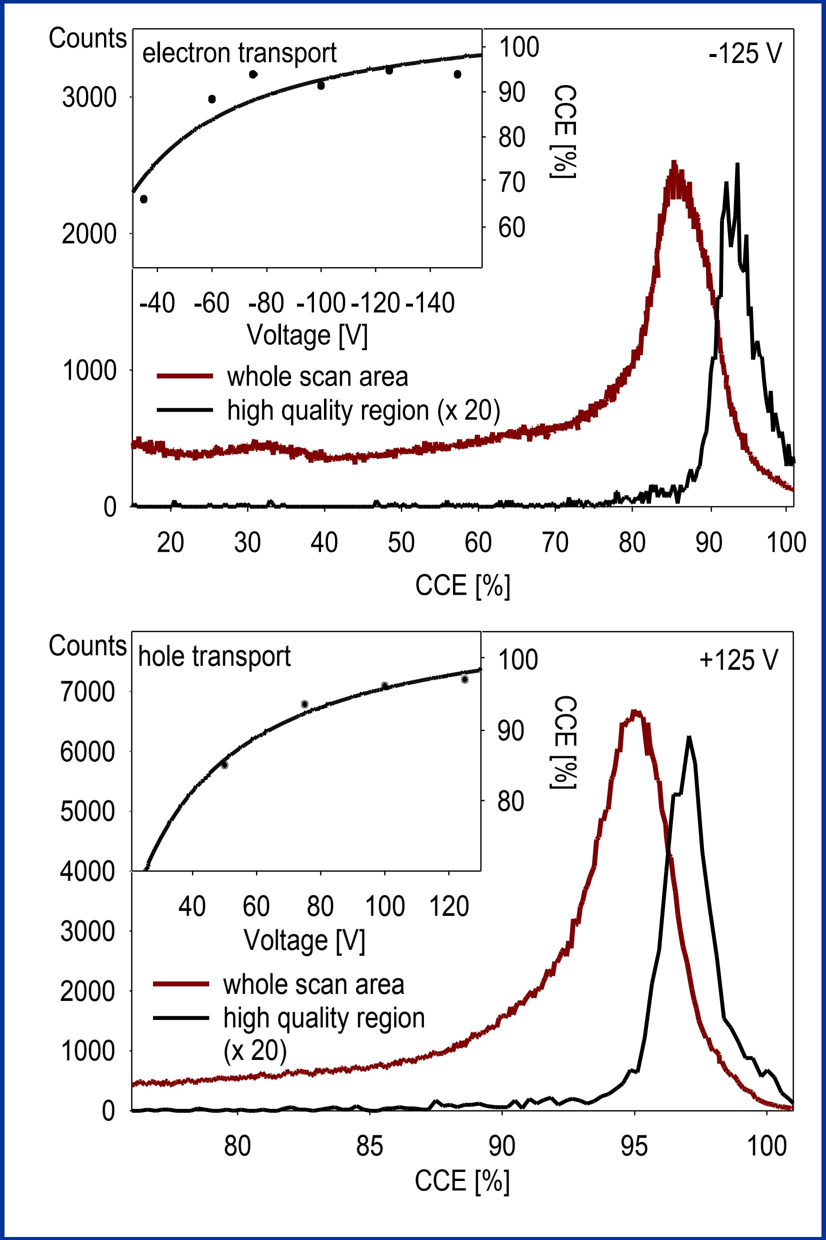


Electrons and holes are affected

- strongly by the nitrogen
- weakly by dislocations

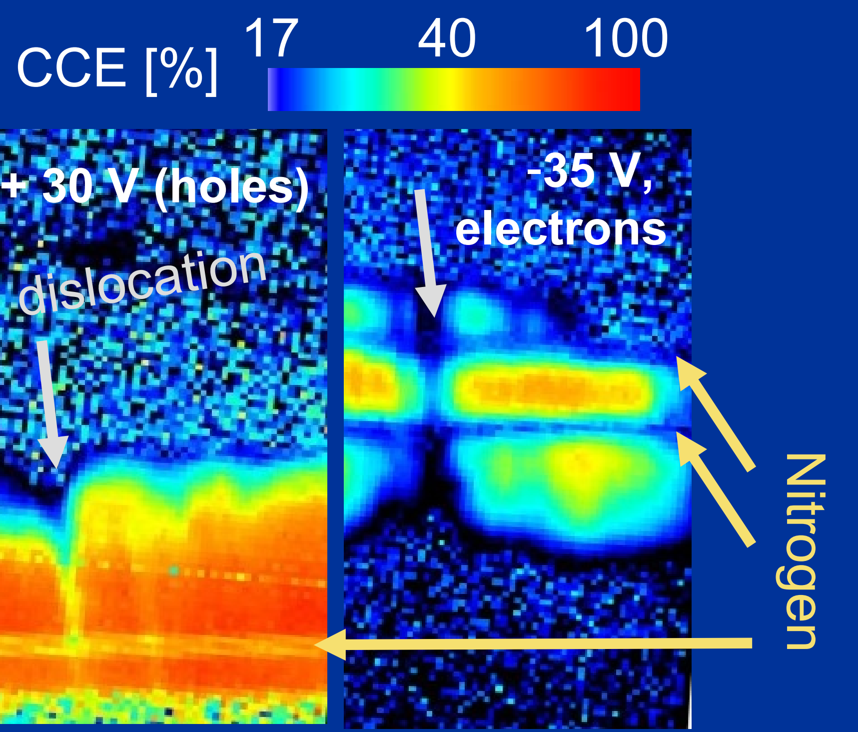
Polarisation/ priming has been observed, especially in hole sensitive transport.

Sample D1: CCE

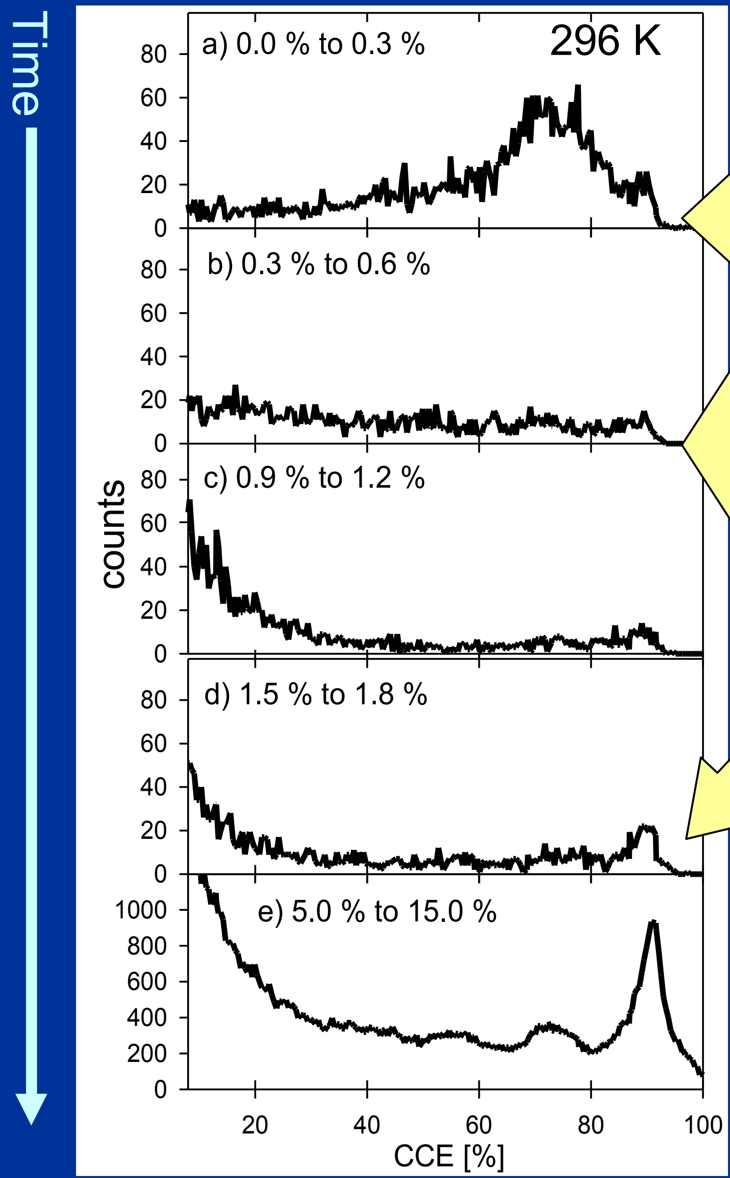


CCE above 90 % for field strength < 2500 Vcm^{-1}

CCE images appear complementary at low bias and change with the growth direction of the crystal.



Polarisation and Priming in D1

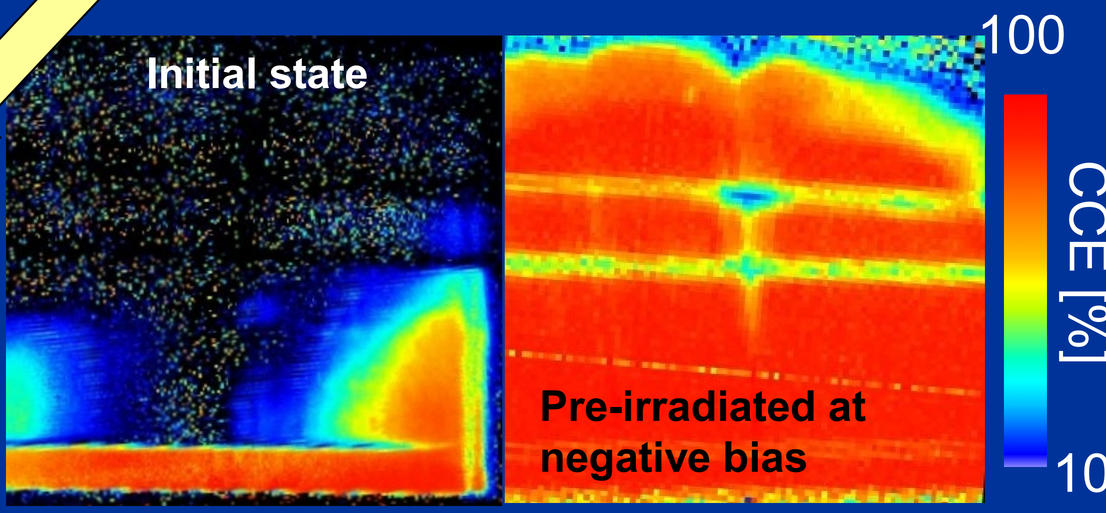


D1 at +100 V, holes 296 K:

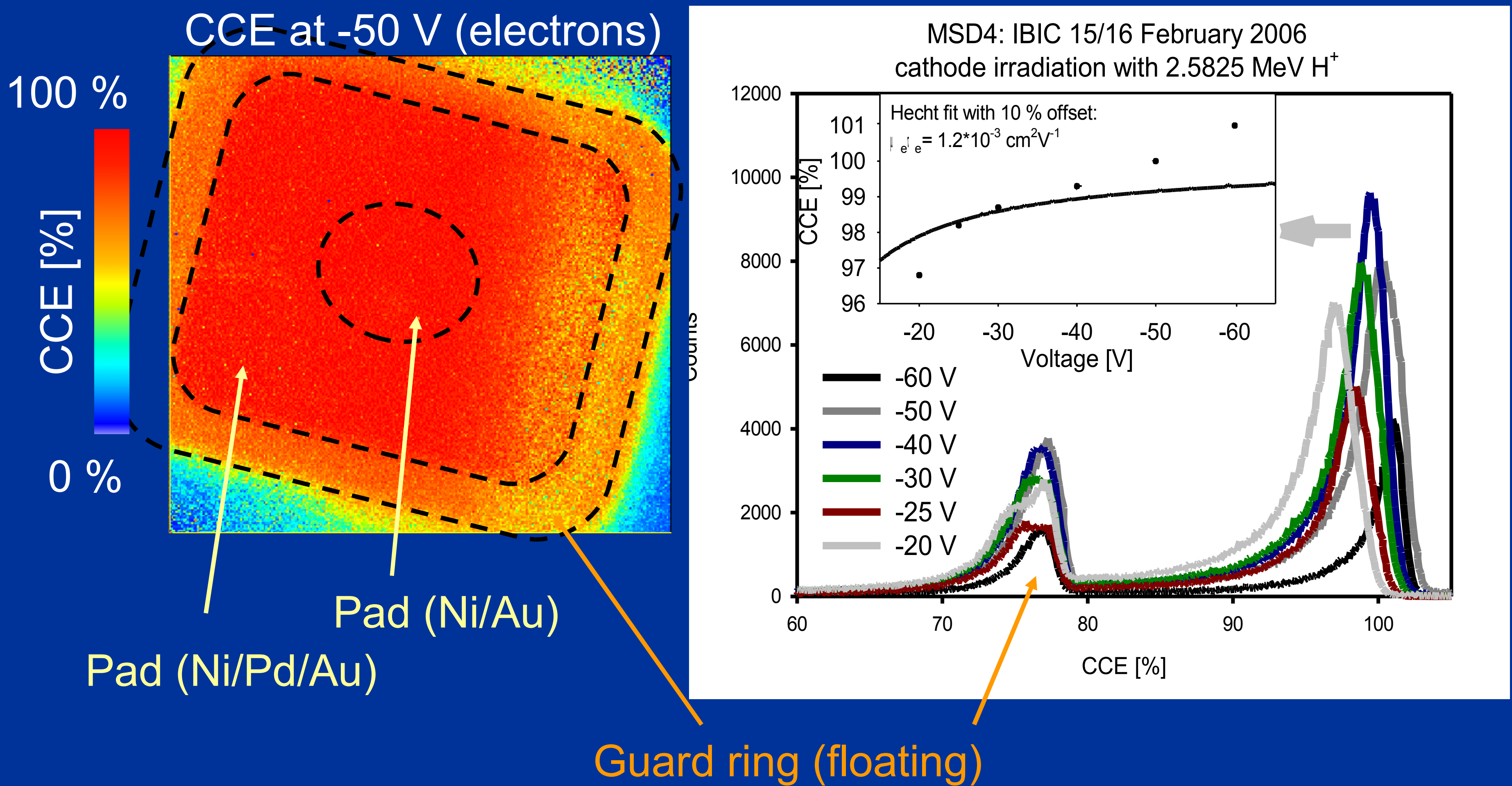
Events registered over the full area

The amplitudes in the upper part of the
image reduce and

finally drop below threshold level

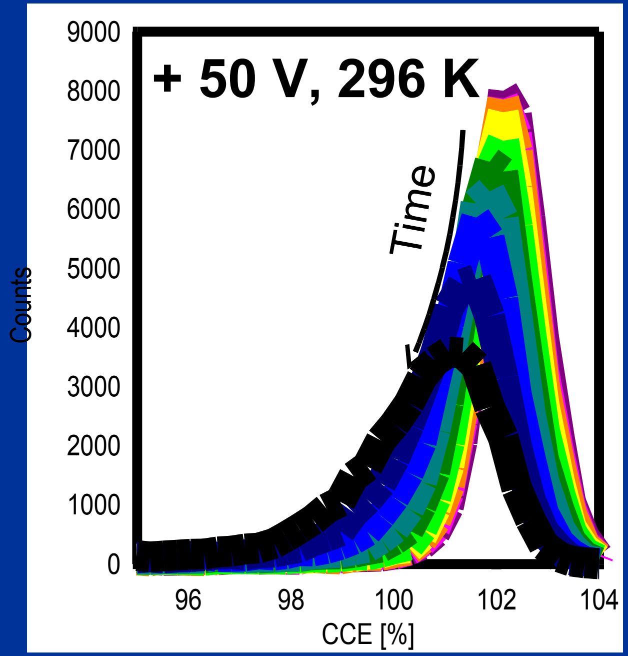


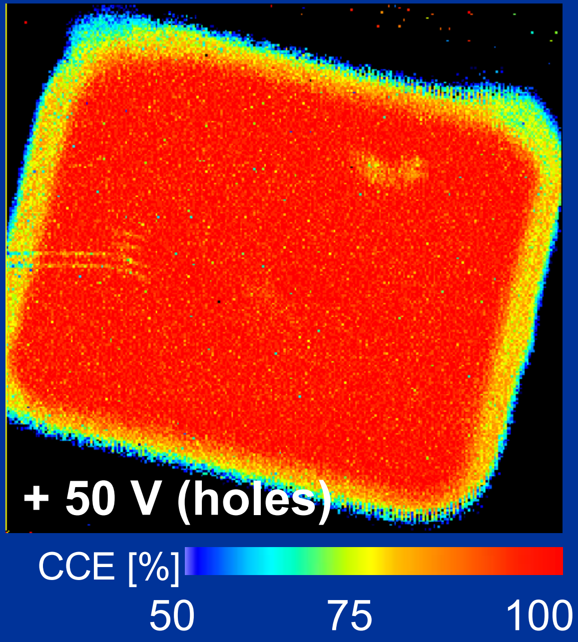
CCE in sample D2: electron transport

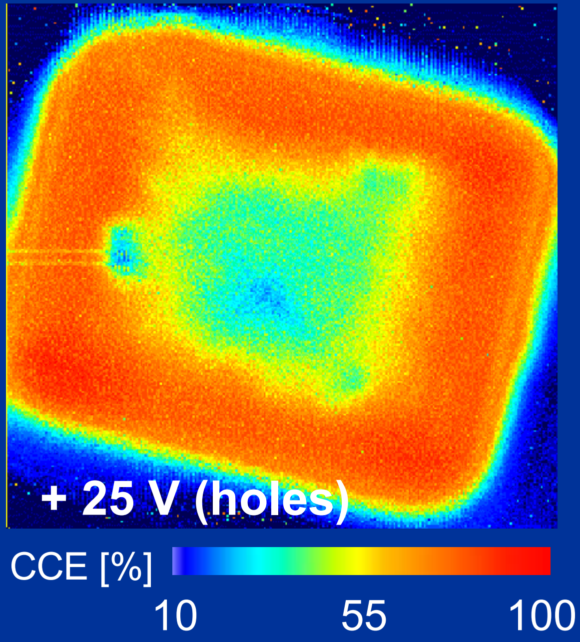


Saturation of CCE at higher value and lower field strength compared to D1:

CCE in sample D2: hole transport

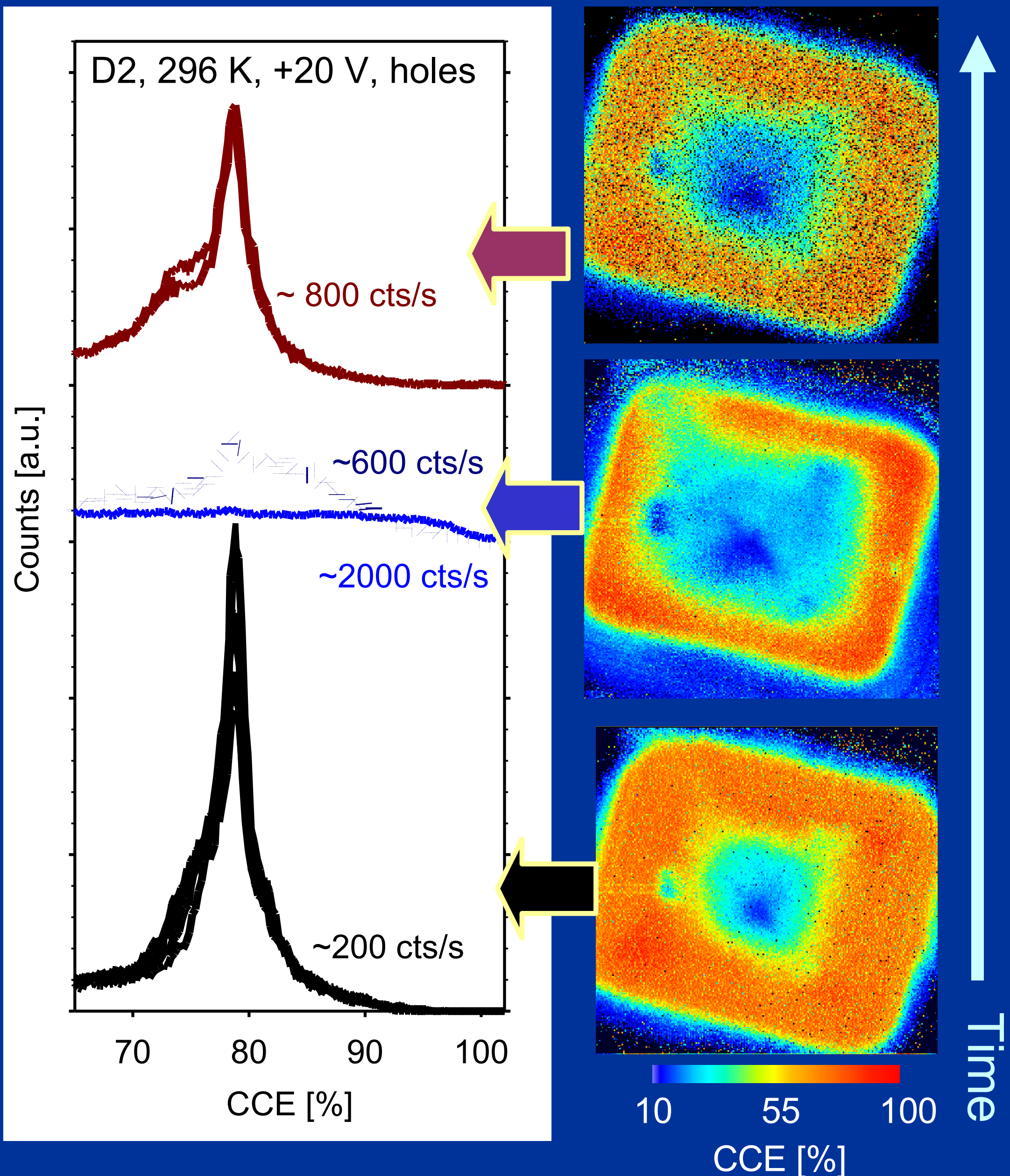






- Very high and narrow peak at +50 V, with very small signs of signal decrease over time.
- The CCE image at low electric field strength seems related to the contact structure.
- At bias voltages below +45 V, the beam current was unstable and the data acquired during these measurements seems not reproducible due to a dose rate dependence of detector response.

Example of varying hole response of D2 at low field

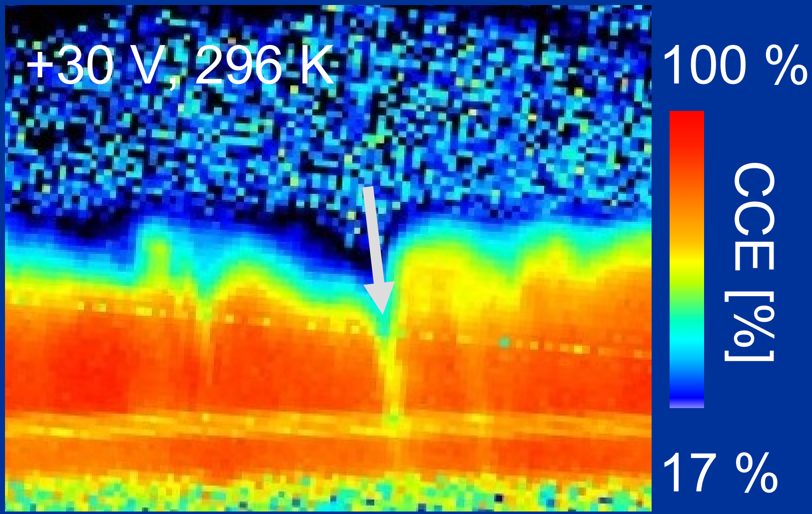


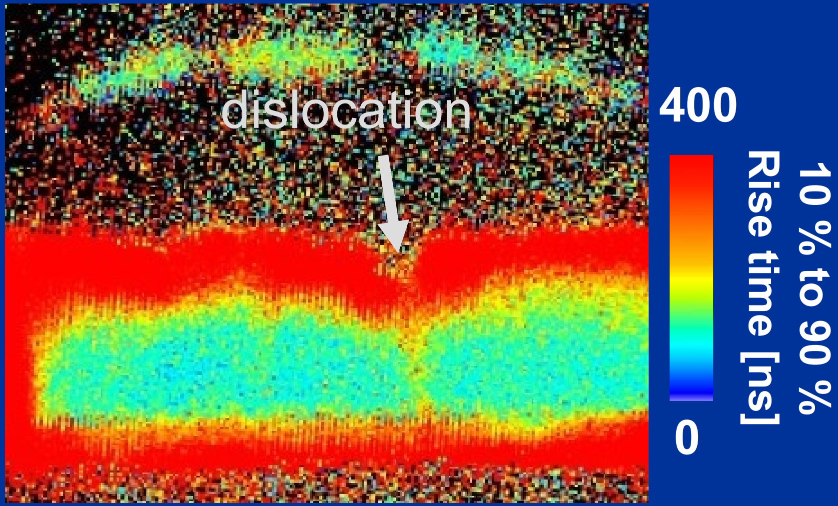
The spectra seem to be able to recover within short periods of time (few minutes).

Highest CCE events are found at high count rate, after a long “break” of irradiation (very low event rate).

Maximum CCE in the corners – geometric effect?

Digital IBIC in D1





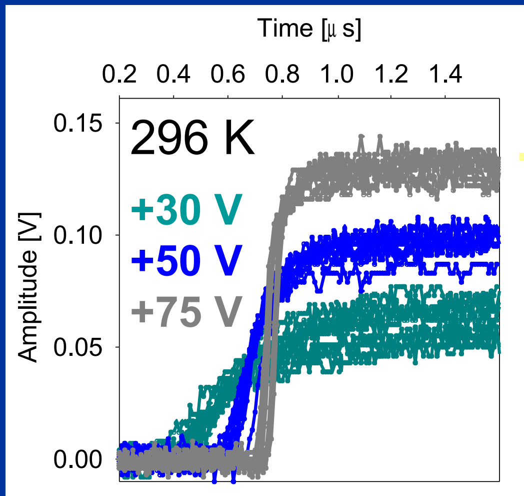
Minimum av. risetime (system response): ~80 ns

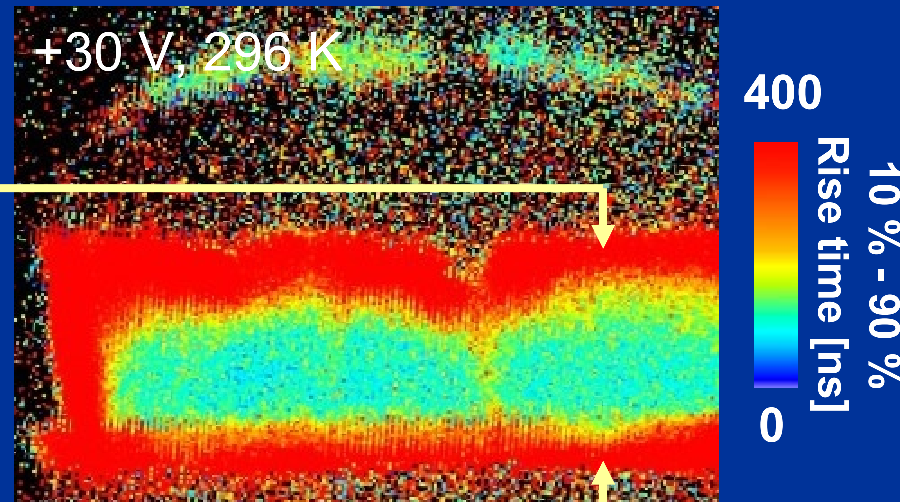
- No rise time variation was found for electron sensitive pulses and in sample D2, where the transit time/lifetime is expected to be shorter or similar than the system resolution:

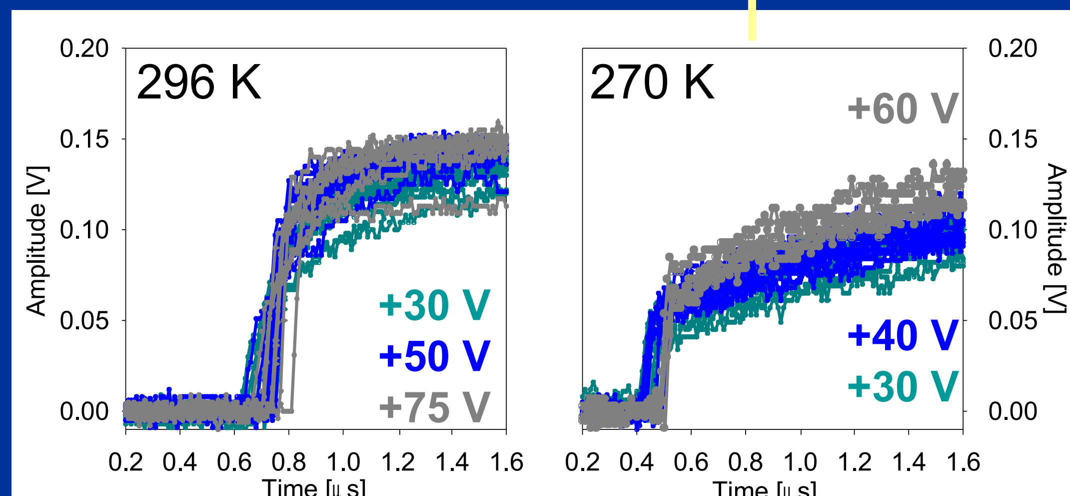
$$T_R = \frac{d^2}{V\mu} \qquad \mu > 1000 \frac{\text{cm}^2}{\text{V}}$$

- There is not a direct correlation between rise time and CCE.
- Effect of the dislocation lines on the pulse shapes could not be confirmed.

Separation of detrapping and priming effects



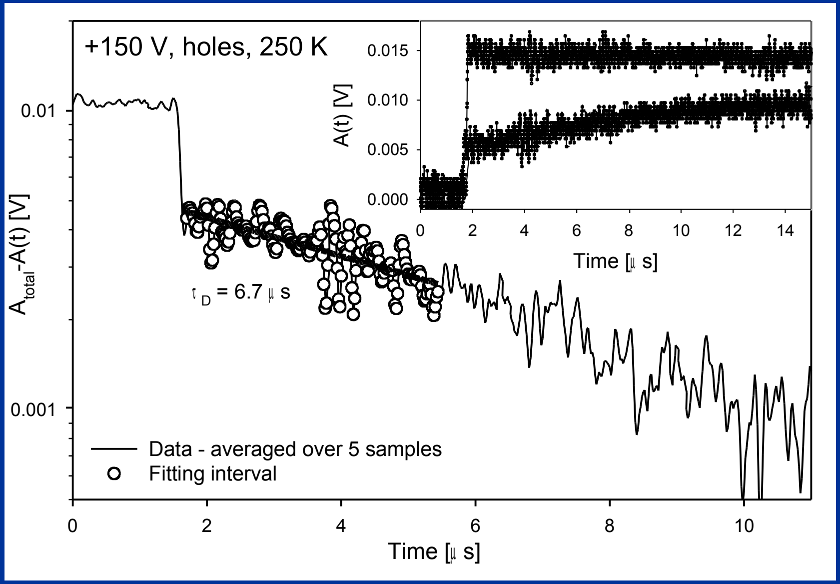


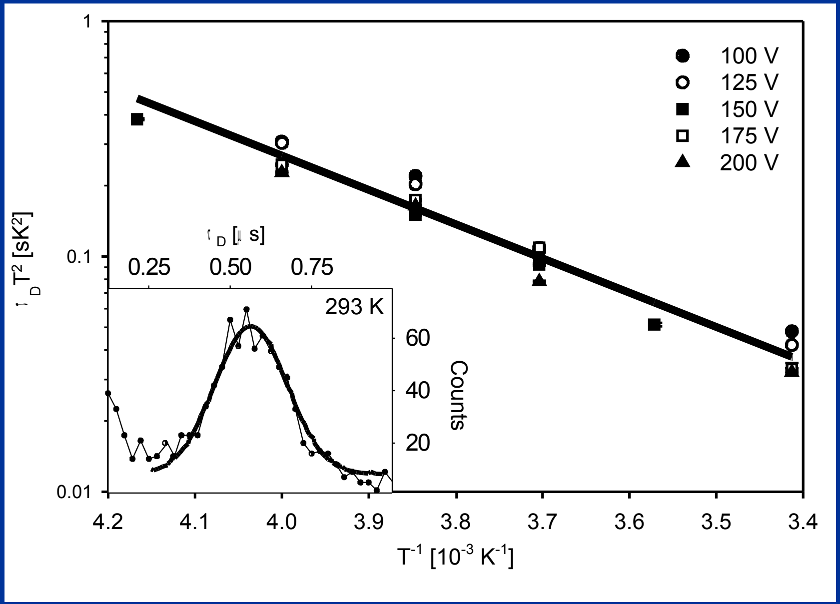


The rise time changes with bias voltage and not with temperature, e.g. not affected by de-trapping of carriers, confirming spatial variation of field strength.

The de-trapping effect is temperature, but only weakly voltage dependent (is boron introduced from the substrate ?)

Activation energy of the shallow trap in D1





If multiple trapping and de-trapping can be neglected, then

$$\ln\left(A_{total} - a(t)\right) = const - \frac{t}{\tau_D}$$

Similar level identified in nominally undoped and B - doped, single and polycrystalline diamond with E_A values between 0.29 eV and 0.4 eV.

Glesener *et al*, Appl. Phys. Lett. 63 (1993) 769
Sato *et al*, Diamond Relat. Mater 7 (1998) 1167
Marinelli *et al*, Diamond Relat. Mater. 12 (2003) 1733
Wang *et al*, Appl. Phys. Lett. 88 (2006) 23501
Balducci *et al*, Appl. Phys. Lett. 87 (2005) 222101

Conclusion & Summary

- Degradation of electron and hole transport is correlated to the observed nitrogen and band A luminescence signals (recombination centre ?) in D1.

- A shallow trap level, possibly boron related, was found close to the HTHP substrate interface of the sample.

- The vertically cut sample D1 with symmetric contacts showed stronger influence of polarisation and priming on hole transport than on electrons over “long” timescales. The effect seems to follow the growth direction of the material.

- In contrast, D2 shows hardly any polarisation or priming, but an event rate dependence of the signal at low bias voltages (may be possible for electrons and D1 too?). The CCE image seems correlated to the contact geometry of the sample.

Thanks to…

Surrey Ion Beam Centre: I. Gomez-Morilla, C. Jeynes and A. Cansell
G. Hill at Sheffield University
J. Morse, ESRF
Element Six
EPSRC Grant GR/R34486/01
PPARC Grant PP/D507607/1