Characterization of deep centers in semi-insulating SiC and HgI_2: Application of discharge current transient spectroscopy

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Solid-state detector for use in X-ray energy spectroscopy

High-purity Si pin diode and High-purity Ge pin diode

X-rays should be absorbed in a depletion region in the diode.

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High reverse bias is required to form a wide depletion region in the diode.

The reverse current in X-ray diodes should be lower than 1 nA.

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In order to reduce the reverse current to < 1 nA,
these diodes should be cooled down.

Portable X-ray detector operating at room temperature

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Highly resistive HgI_2 and CdTe have been investigated.

Traps in depletion region in diodes

Degradation of performance of X-ray detector

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It is necessary to investigate traps in highly resistive semiconductors

Methods for determining densities and energy levels of traps

1. Transient capacitance methods
   A. Deep Level Transient Spectroscopy (DLTS)
   B. Isothermal Capacitance Transient Spectroscopy (ICTS)

In low-resistivity semiconductors

Capacitance determined by the depletion region in the diode can be measured.

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DLTS and ICTS are applicable to characterization of traps.

Semi-insulating semiconductor

Measured capacitance is a capacitance determined by the thickness of the diode, not by the depletion region in the junction.

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DLTS and ICTS are not applicable.

Transient current due to emission of charged carriers from traps can be used for determining densities and emission rates of traps in semi-insulating semiconductors.

Transient current methods

Thermally stimulated current (TSC)

Current due to emission of charged carriers from traps is measured, as temperature increases from low temperature.

Problems:

1. Case of existing traps with close emission rates
2. Effect of pyroelectric current
3. Temperature-dependent leakage current

Isothermal measurement is suitable.

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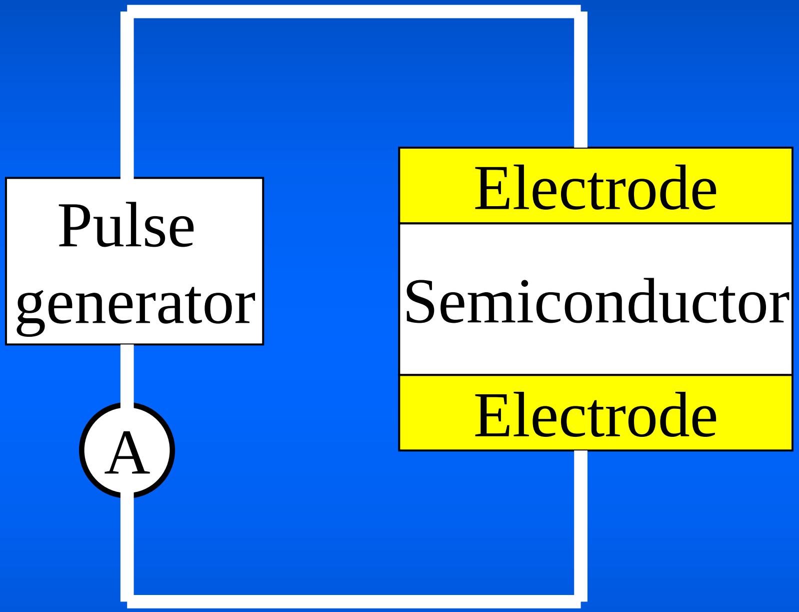
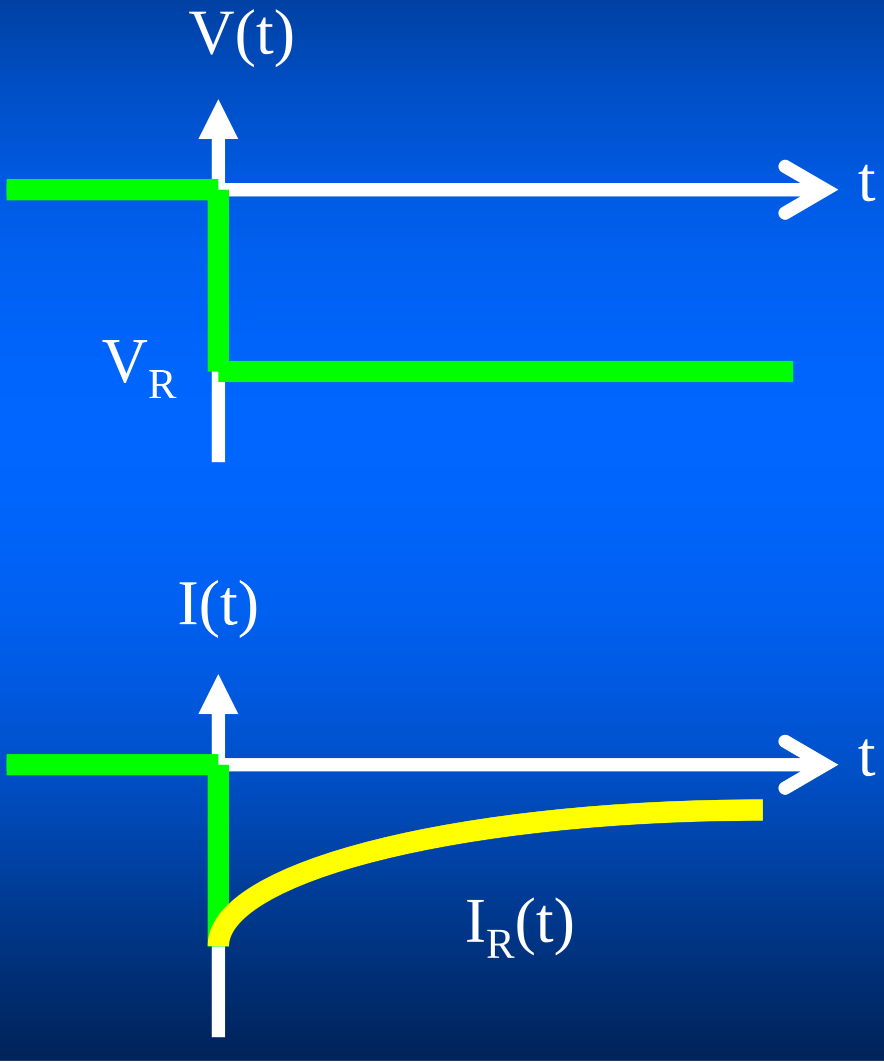
Discharge Current Transient Spectroscopy (DCTS)

DCTS (Discharge Current Transient Spectroscopy)





Transient reverse current $I_R(t)$

$$I_{\mathrm{R}}(t) = I_{\mathrm{TR}}(t) + I_{\mathrm{SR}}$$

1. Transient current : $I_{TR}(t)$
2. Steady-state reverse current : I_{SR}

Total charge of trapped carriers in diode

$$Q(t) = S\sum_i qN_{ti}\exp\left(-e_{ti}t\right)$$

N_{ti} : i-th trap density per unit area

e_{ti} : i-th trap emission rate

S : Junction area

Transient current

$$I_{\mathrm{TR}}(t) = -\frac{\mathrm{d}Q(t)}{\mathrm{d}t} = S\sum_i qN_{ti}e_{ti}\exp\left(-e_{ti}t\right)$$

Definition of DCTS signal

$$D\left(t, e_{\mathrm{ref}}\right) \equiv \frac{t}{qS}\left[I_{\mathrm{R}}(t) - I_{\mathrm{SR}}\right]\exp\left(-e_{\mathrm{ref}}t + 1\right)$$

e_{ref} : peak-shift parameter

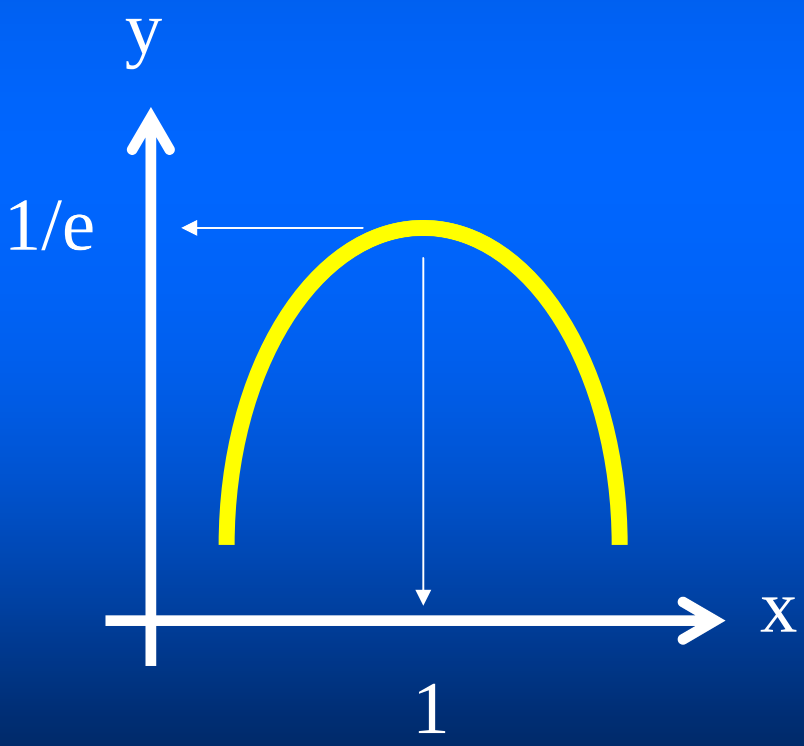
Theoretically derived DCTS signal

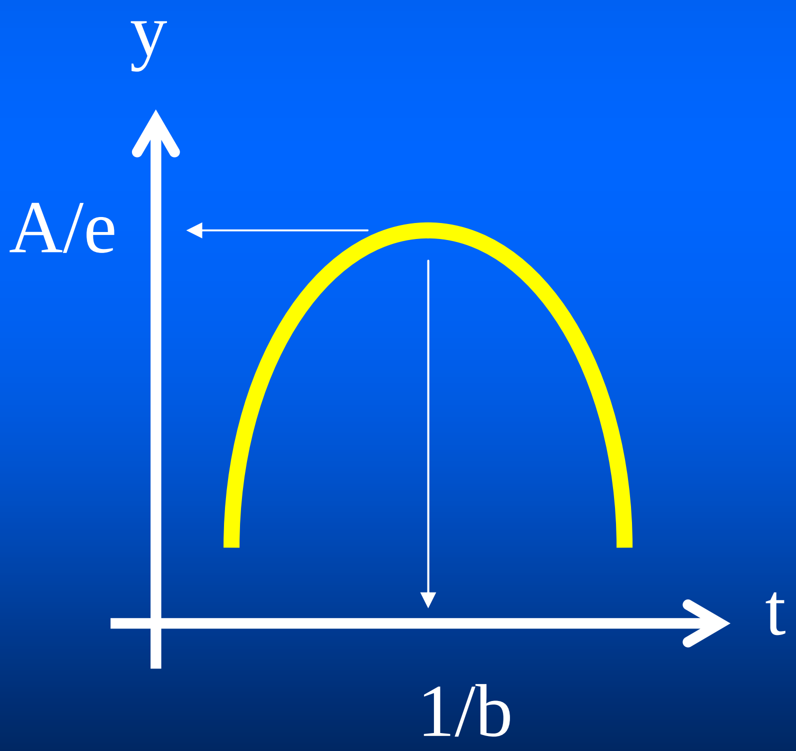
$$D\left(t, e_{\mathrm{ref}}\right) = \frac{t}{qS} I_{\mathrm{TR}}(t)\exp\left(-e_{\mathrm{ref}}t + 1\right)$$

$$= \sum_{i} N_{\mathrm{t}i} e_{\mathrm{t}i} t \exp\left[-\left(e_{\mathrm{t}i} + e_{\mathrm{ref}}\right)t + 1\right]$$

$$y = x\exp(-x) \qquad y = Abt\exp(-bt)$$

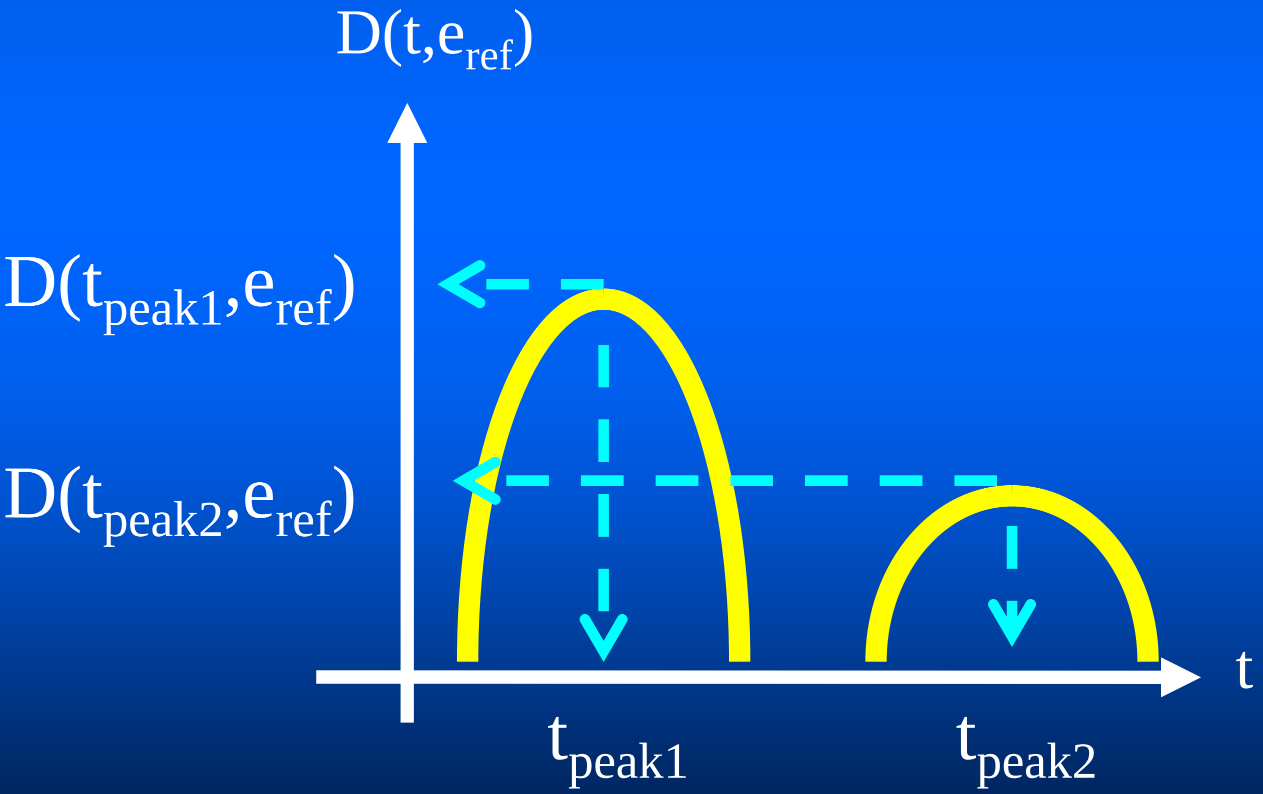
Maximum at $x = 1$ Maximum at $bt = 1$





Peak of DCTS signal

$$D(t, e_{\mathrm{ref}}) = \sum_i N_{ti} e_{ti} t \exp[-(e_{ti} + e_{\mathrm{ref}})t + 1]$$



i-th trap

Emission rate

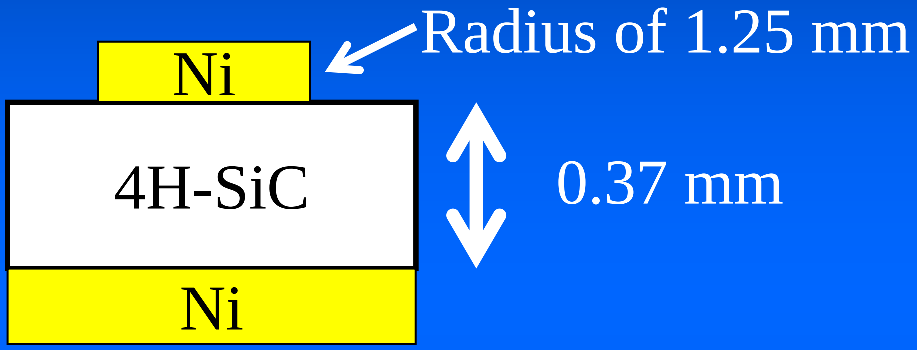
$$e_{ti} = \frac{1}{t_{\mathrm{peak}i}} - e_{\mathrm{ref}}$$

Density

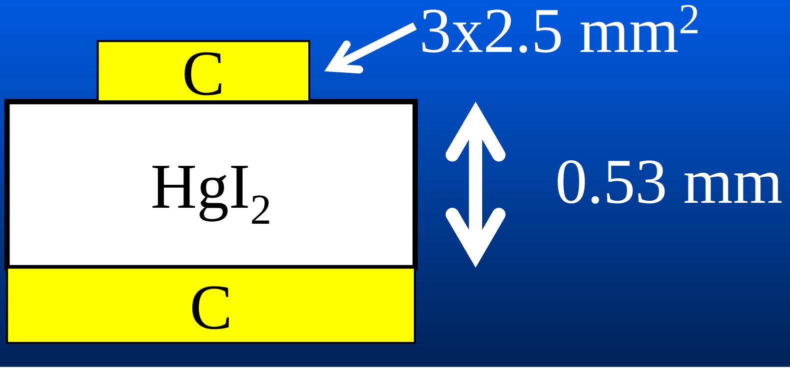
$$N_{ti} = \frac{D(t_{\mathrm{peak}i}, e_{\mathrm{ref}})}{1 - e_{\mathrm{ref}} t_{\mathrm{peak}i}}$$

Samples

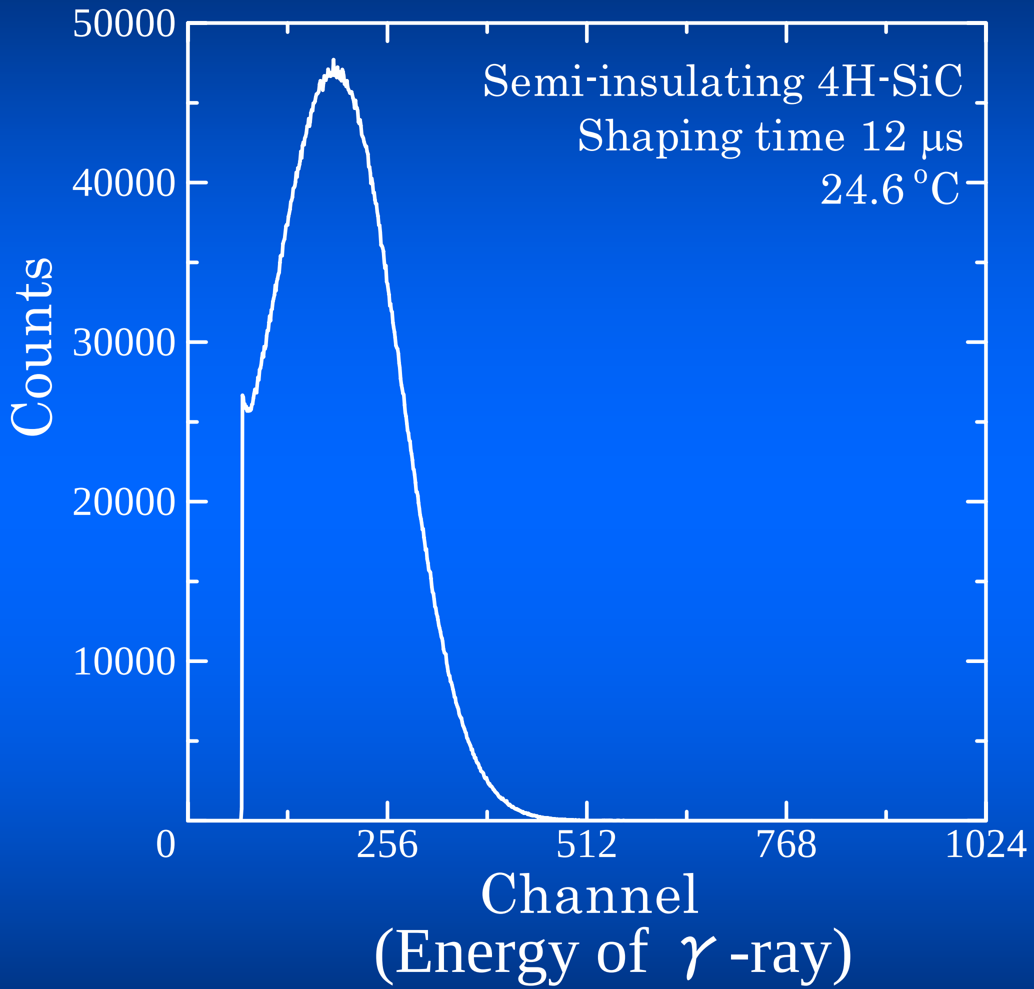
High-purity semi-insulating 4H-SiC



Semi-insulating HgI_2



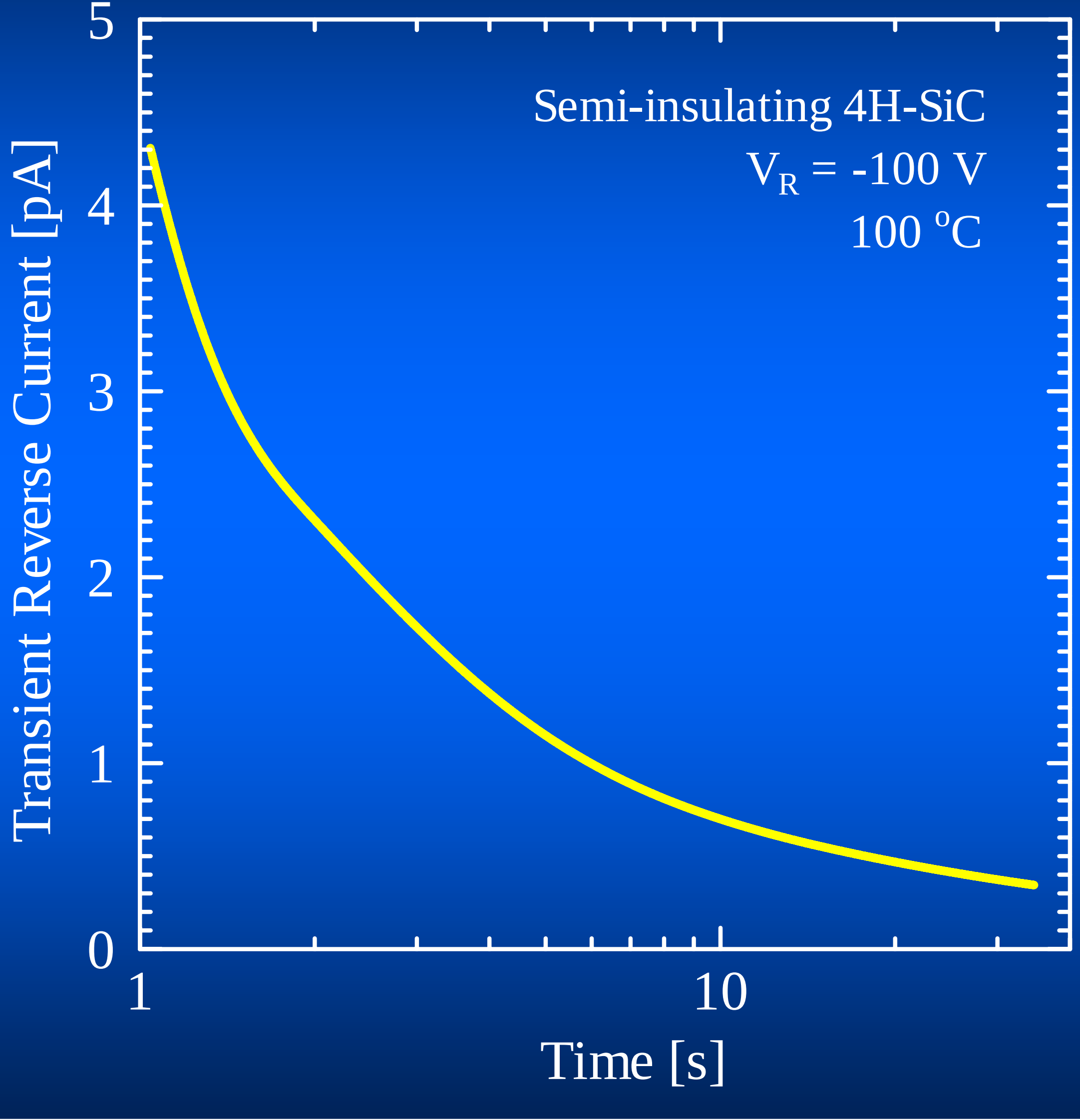
γ -ray spectrum from ^{241}Am



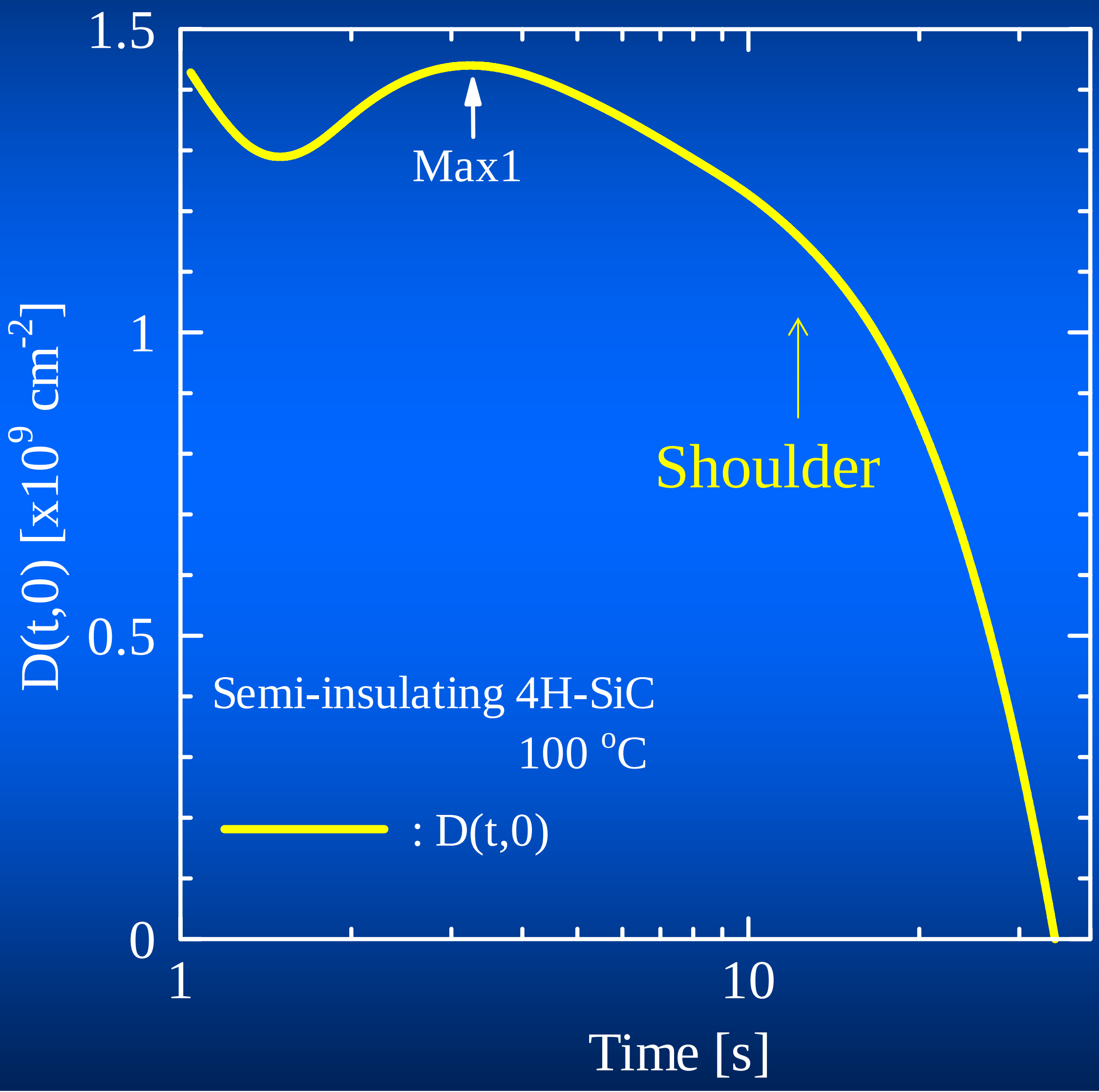
High-purity semi-insulating 4H-SiC diode can detect γ -ray

High-purity semi-insulating 4H-SiC

Transient reverse current



High-purity semi-insulating 4H-SiC



DCTS signal with **e_{ref}=0 eV**

Max1 (Peak)

$$t_{peak1} = 3.2 \text{ s}$$

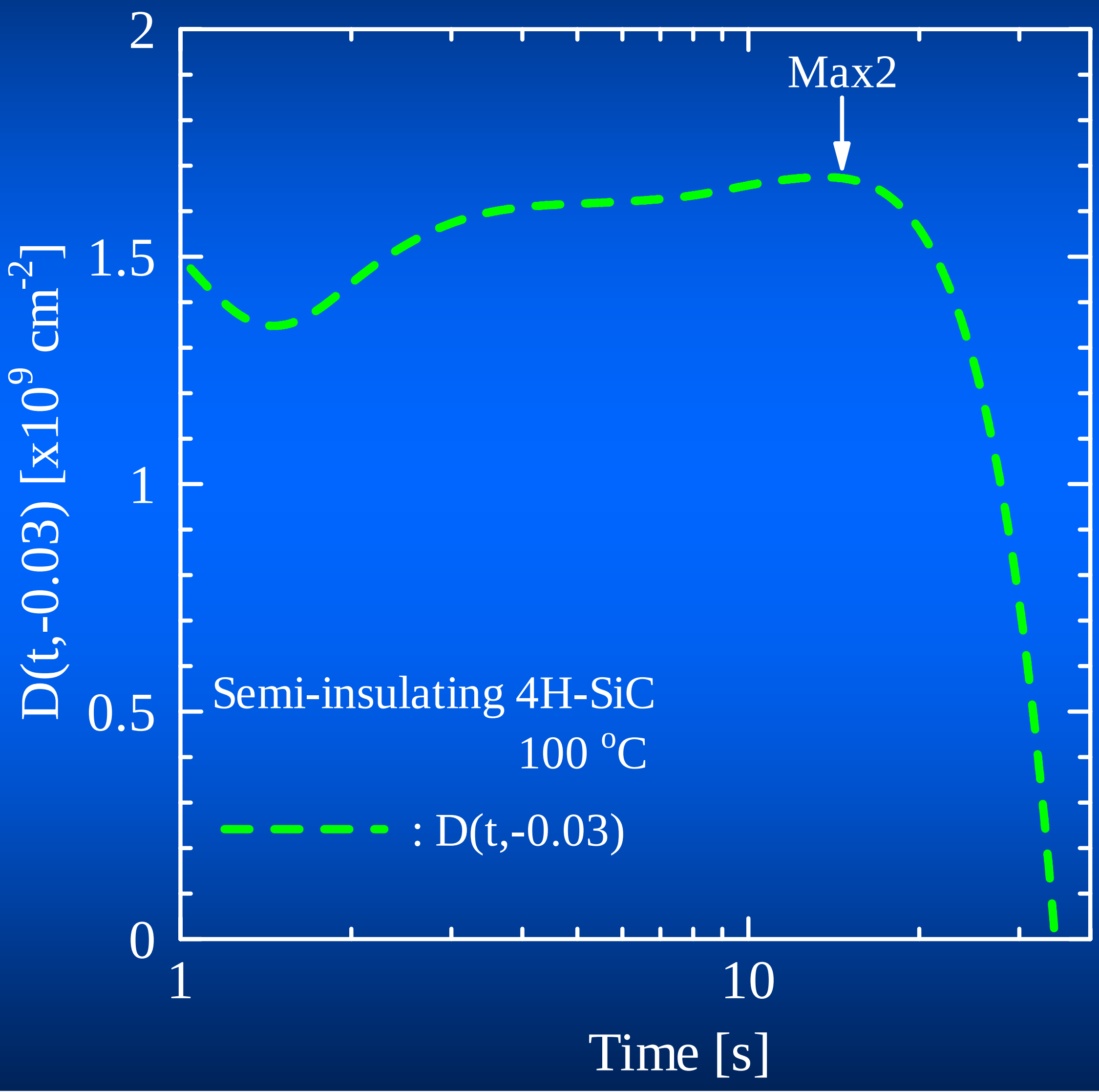
$$D(t_{peak1},0) = 1.4\times10^{9}\ \text{cm}^{-2}$$

↓

$$e_{t1} = 0.31\ \text{s}^{-1}$$

$$N_{t1} = 1.4\times10^{9}\ \text{cm}^{-2}$$

High-purity semi-insulating 4H-SiC



DCTS signal

with **e_{ref}=-0.03 eV**

Max2 (Peak)

$$t_{\mathrm{peak}\,2} = 13.5\ \mathrm{s}$$

$$D(t_{\mathrm{peak}\,2}, 0) = 1.7 \times 10^{9}\ \mathrm{cm}^{-2}$$

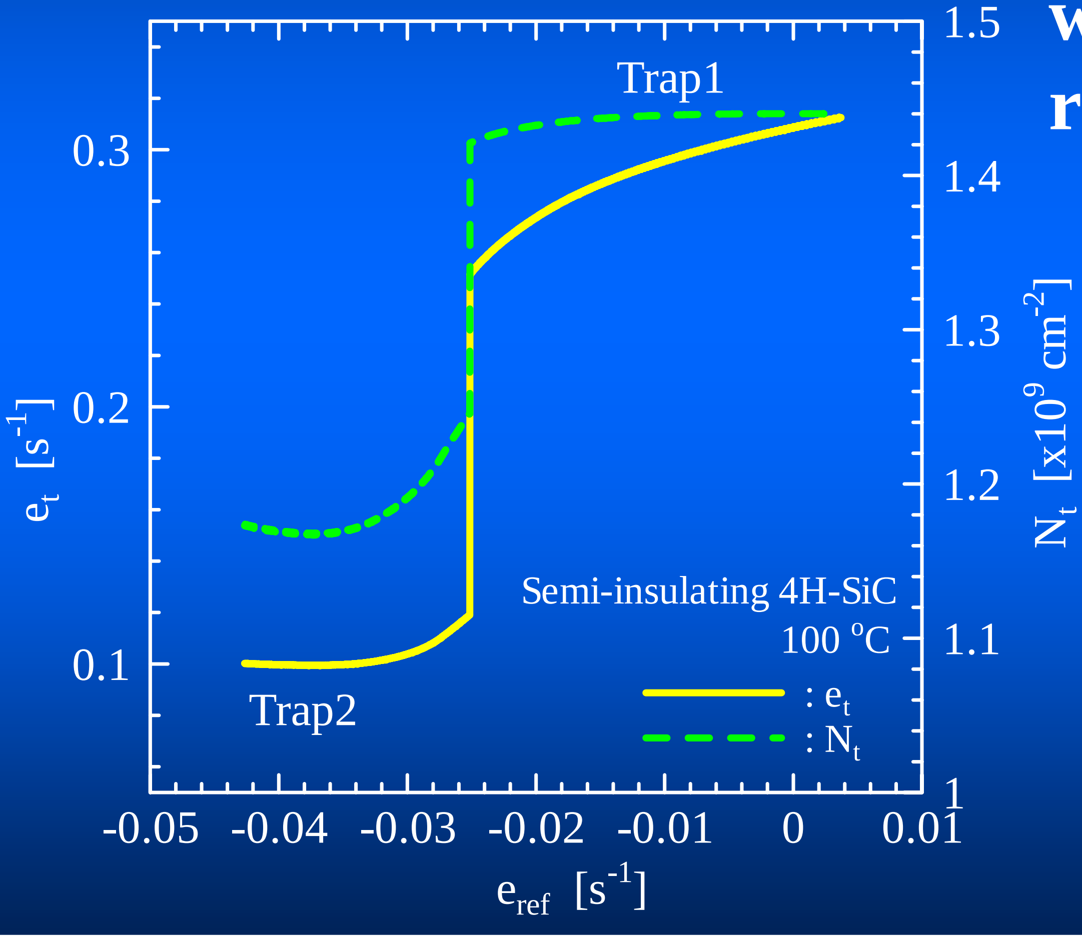
↓

$$e_{t2} = 0.10\ \mathrm{s}^{-1}$$

$$N_{t2} = 1.2 \times 10^{9}\ \mathrm{cm}^{-2}$$

High-purity semi-insulating 4H-SiC

e_{ref} dependence



Two types of trap species with discrete emission rates

Trap1

$$e_{t1} = 0.282 \pm 0.03\ \mathrm{s}^{-1}$$

$$N_{t1} = (1.43 \pm 0.01) \times 10^9\ \mathrm{cm}^{-2}$$

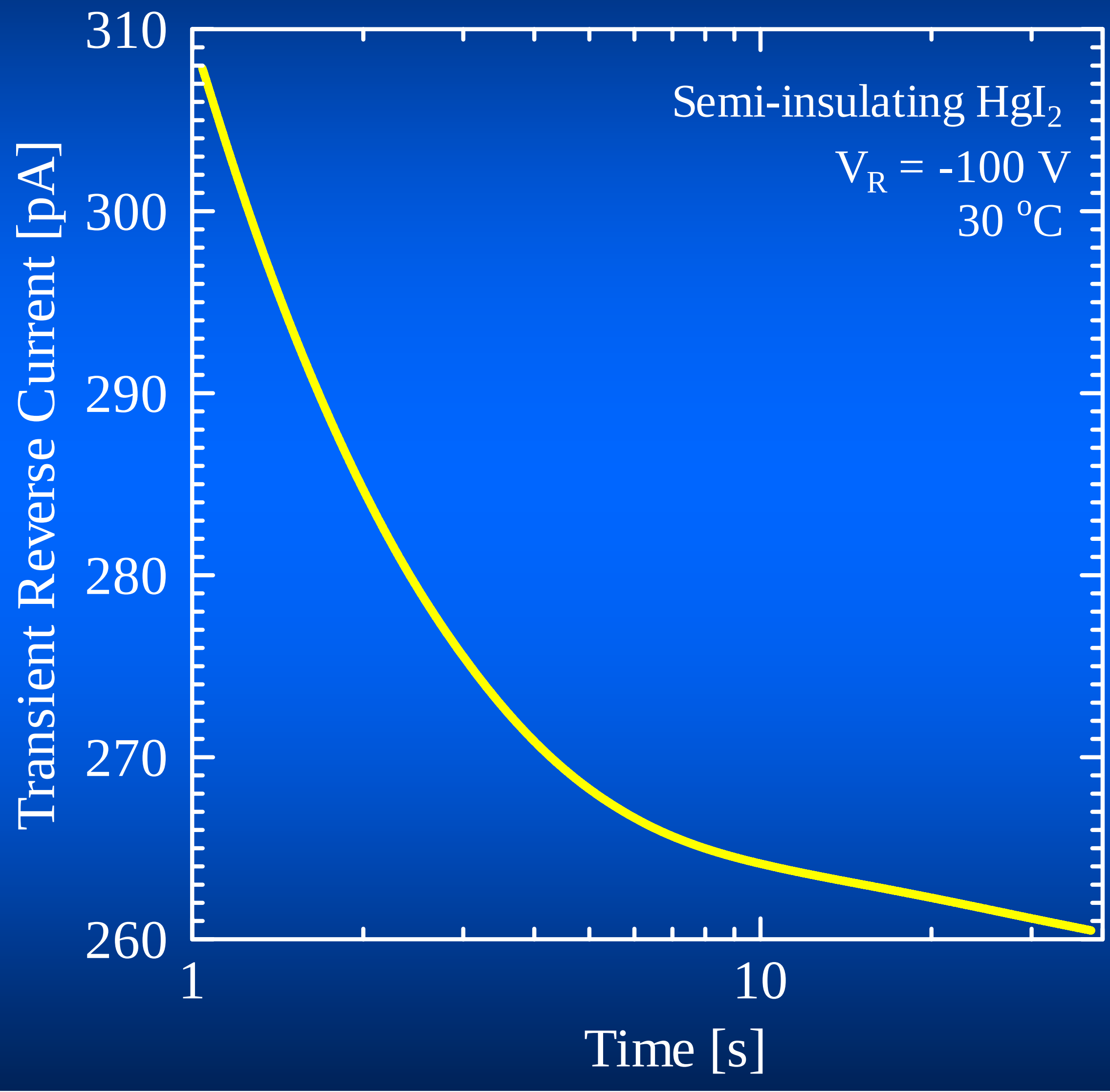
Trap2

$$e_{t2} = 0.110 \pm 0.010\ \mathrm{s}^{-1}$$

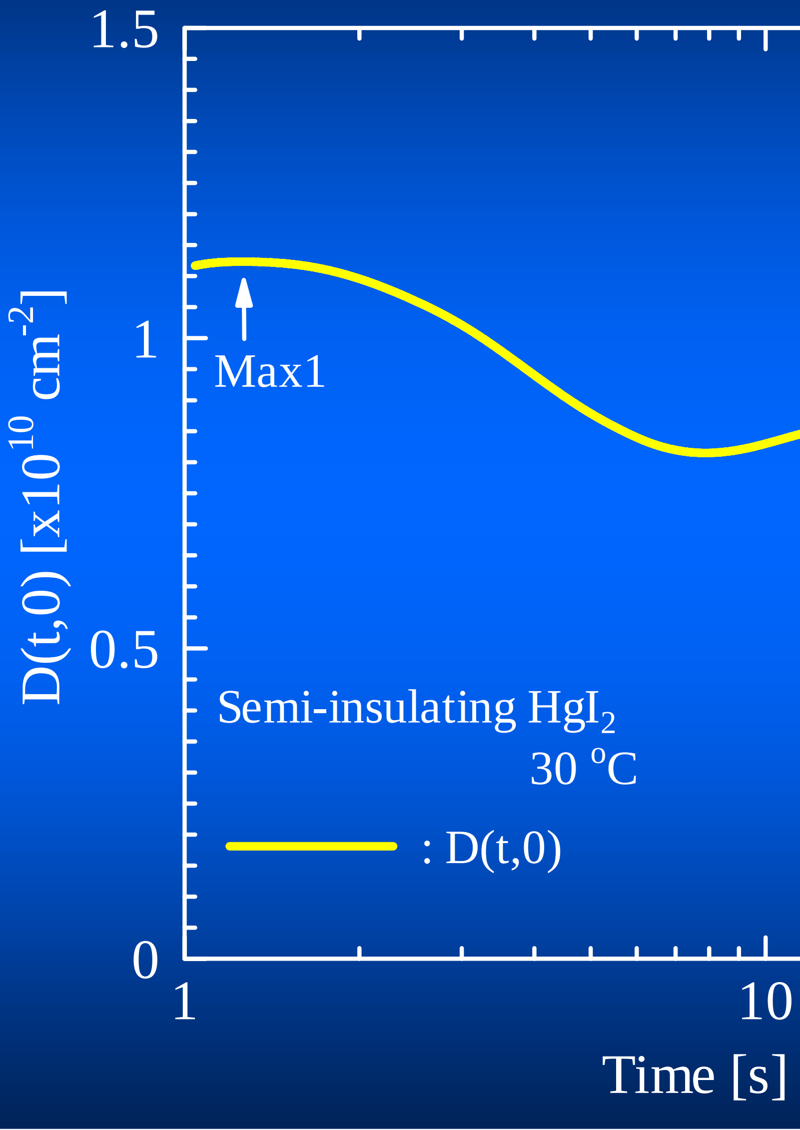
$$N_{t2} = (1.21 \pm 0.04) \times 10^9\ \mathrm{cm}^{-2}$$

Semi-insulating HgI_2

Transient reverse current



Semi-insulating HgI_2



DCTS signal with **e_{ref}=0 eV**

peak

$$t_{peak1} = 1.3 \ \text{s}$$

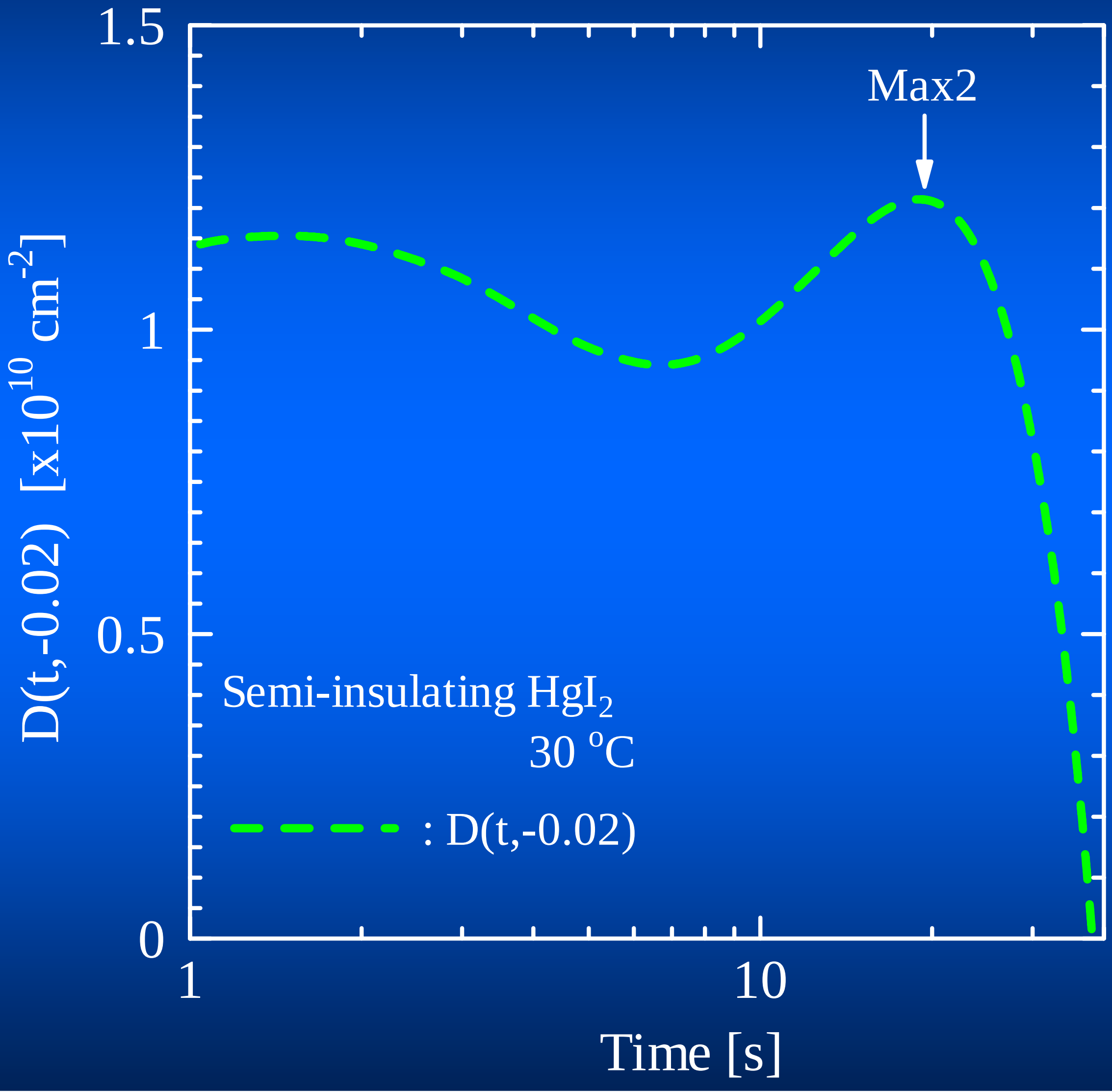
$$D\left(t_{peak1},0\right) = 1.1\times10^{10} \ \text{cm}^{-2}$$

$$\Downarrow$$

$$e_{t1} = 0.80 \ \text{s}^{-1}$$

$$N_{t1} = 1.1\times10^{10} \ \text{cm}^{-2}$$

Semi-insulating HgI_2



DCTS signal

with **e_{ref}=-0.02 eV**

peak

$$t_{peak2} = 19.0 \text{ s}$$

$$D(t_{peak2}, 0) = 1.2 \times 10^{10} \text{ cm}^{-2}$$

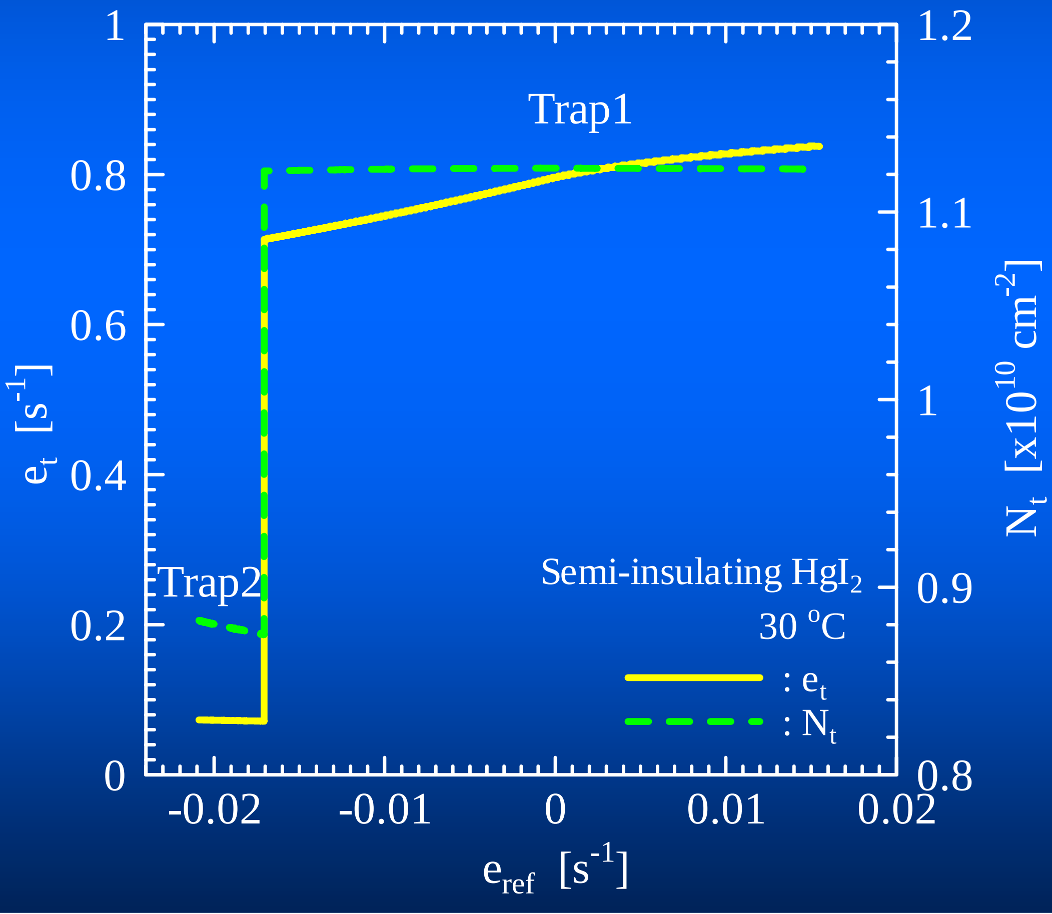
↓

$$e_{t2} = 0.073 \text{ s}^{-1}$$

$$N_{t2} = 8.8 \times 10^{9} \text{ cm}^{-2}$$

Semi-insulating HgI_2

e_{ref} dependence



Two discrete trap species

Trap1

$$e_{t1} = 0.776 \pm 0.062\ \mathrm{s}^{-1}$$

$$N_{t1} = 1.12 \times 10^{9}\ \mathrm{cm}^{-2}$$

Trap2

$$e_{t2} = 0.0723 \pm 0.0009\ \mathrm{s}^{-1}$$

$$N_{t2} = (8.78 \pm 0.04) \times 10^{9}\ \mathrm{cm}^{-2}$$

Summary

1. DCTS based on the transient reverse current in a diode was applied to determining the densities and emission rates of traps in semi-insulating 4H-SiC and HgI_2.
2. DCTS could distinguish between trap species even with discrete close emission rates.

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