Negative muon spin rotation study of acceptor centers in SiC

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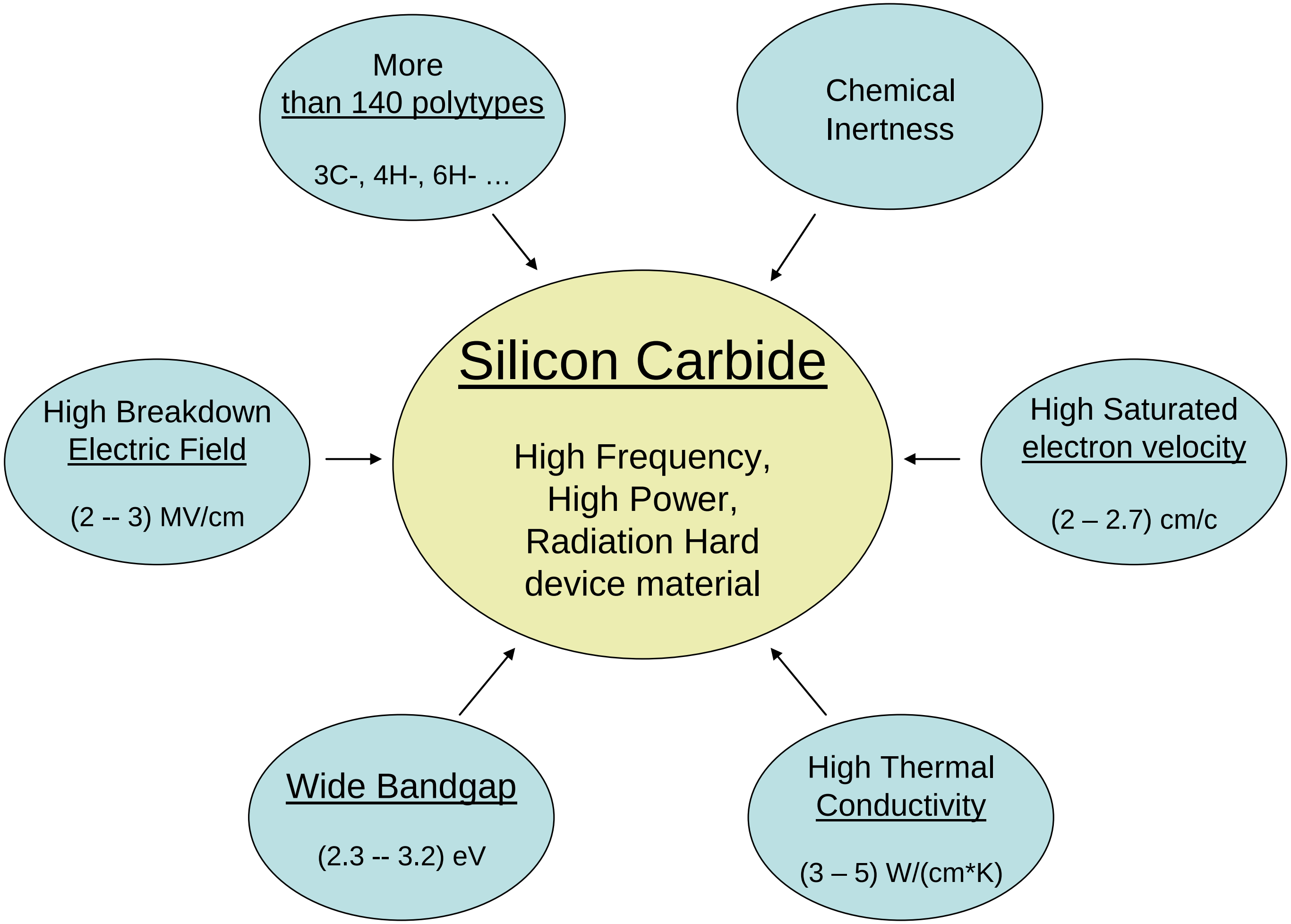


SiC technology: 1) Modified Lely method – substrates (up to 3” in diameter);

2) CVD method – epitaxy.

Donor and acceptor impurities in SiC

Impurity	Type	E_i, mV	Structure
N	shallow donor	50 -- 150	N_C (in-center)
Al	shallow acceptor	240	Al_{Si} (in-center)
B	shallow acceptor	300	B_{Si} (off-center)
Al	deep acceptor	500 – 600	$Al_{Si} + V_C$
B	deep acceptor	600 – 700	$B_{Si} + V_C$

- No ESR-spectra of Al atoms in 3C-SiC were observed;
- No experimental data on the relaxation of the magnetic moment of the Al acceptor;
- No acceptor centers related to a B atom at the C cite were found.

μ^-SR in SiC -- modelling Al_{Si} and B_C substitutional impurities by muonic atoms $_{\mu}Al$ and $_{\mu}B$

Goals: 1) Detect the B_c acceptor

2) Study the relaxation and ionization processes of $_{\mu}Al$ and $_{\mu}B$

Formation of a muonic atom

Slowing down of μ^- implanted into matter

↓

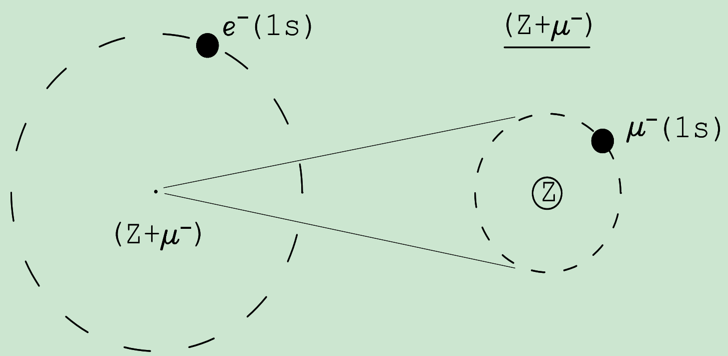
Atomic capture of μ^- : μ^- + Z --> (μ^- + Z)*

↓

De-excitation of the muonic atom

(Auger and radiative transitions of μ^- to the 1S-state)

< 10^{-9} s

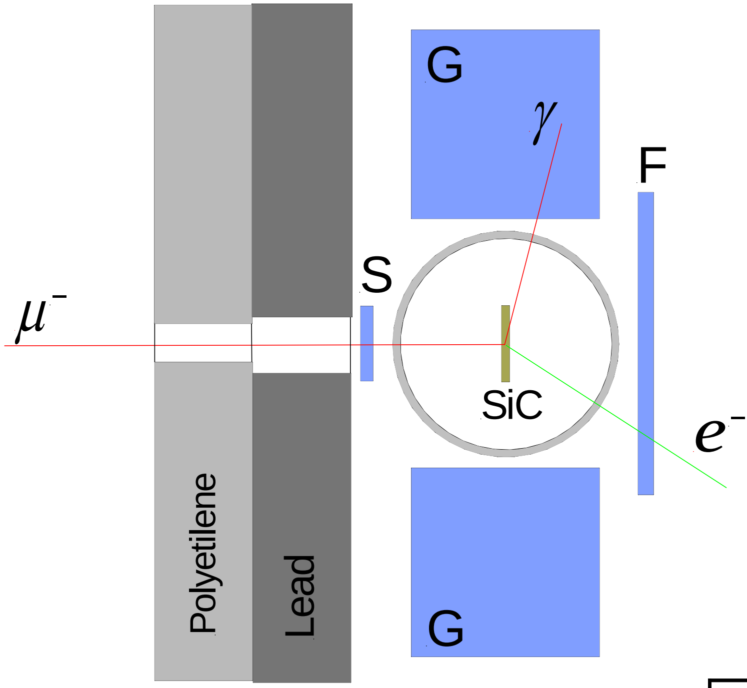


S(Z) = 0 ==> S(Z + μ^-) = 1/2

P(Z + μ^-) = P(μ^-) ~ 17%

SiC: $_{\mu}$Al (760 ns) $_{\mu}$B (2030 ns)

γ-triggered μ^-SR-experiment



S, F – muon and electron counters

G – NaI(Tl) 2” x 2” γ-detectors

Start (Si+C) = S(-F) ==> μ^-SR-spectrum

Start (Si) = SG(-F) ==> γ-trig. μ^-SR-spectrum

Stop = F(-S)

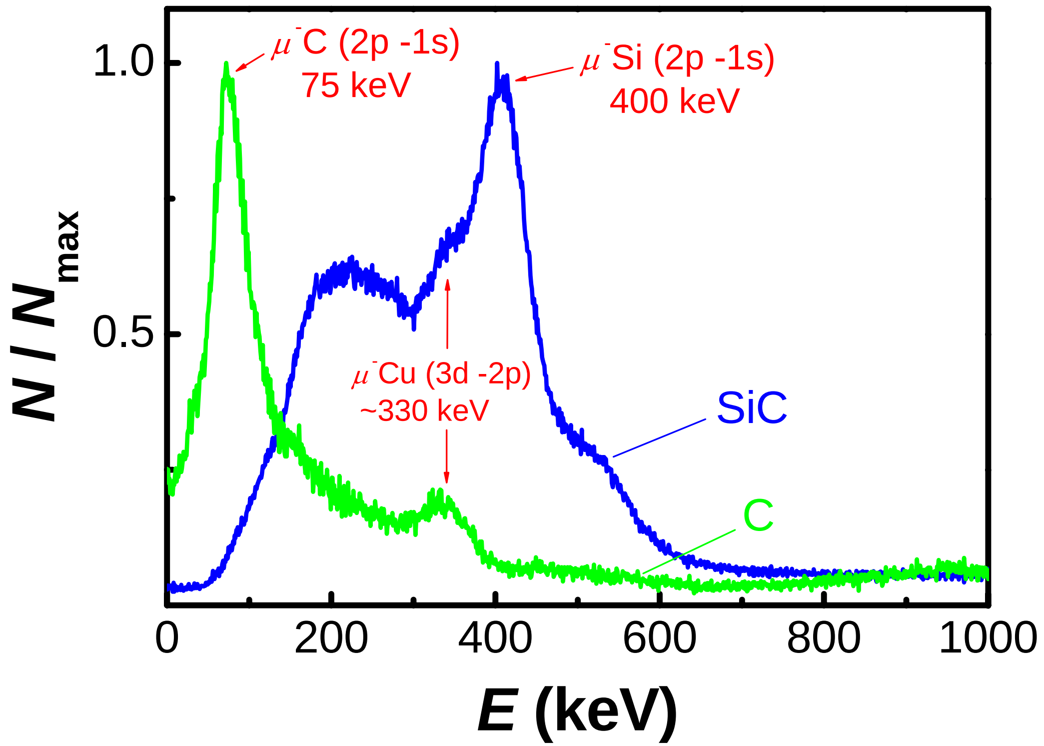
	E_γ (2P→1S) keV	Att. length in Iron mm	Transmission in 2mm Iron %	Overall γ (Si) efficiency %
Si	400	13	85	~10
C	75	2	37	

Sample:

4H-SiC (4x 20x20x0.38 mm³)

n - type (impurity N)

resistivity <0.025 Ohm*cm



Experimental conditions:

TF, H = 1kG, one γ - detector

Effective solid angle of the γ - detector $\approx$ 5%

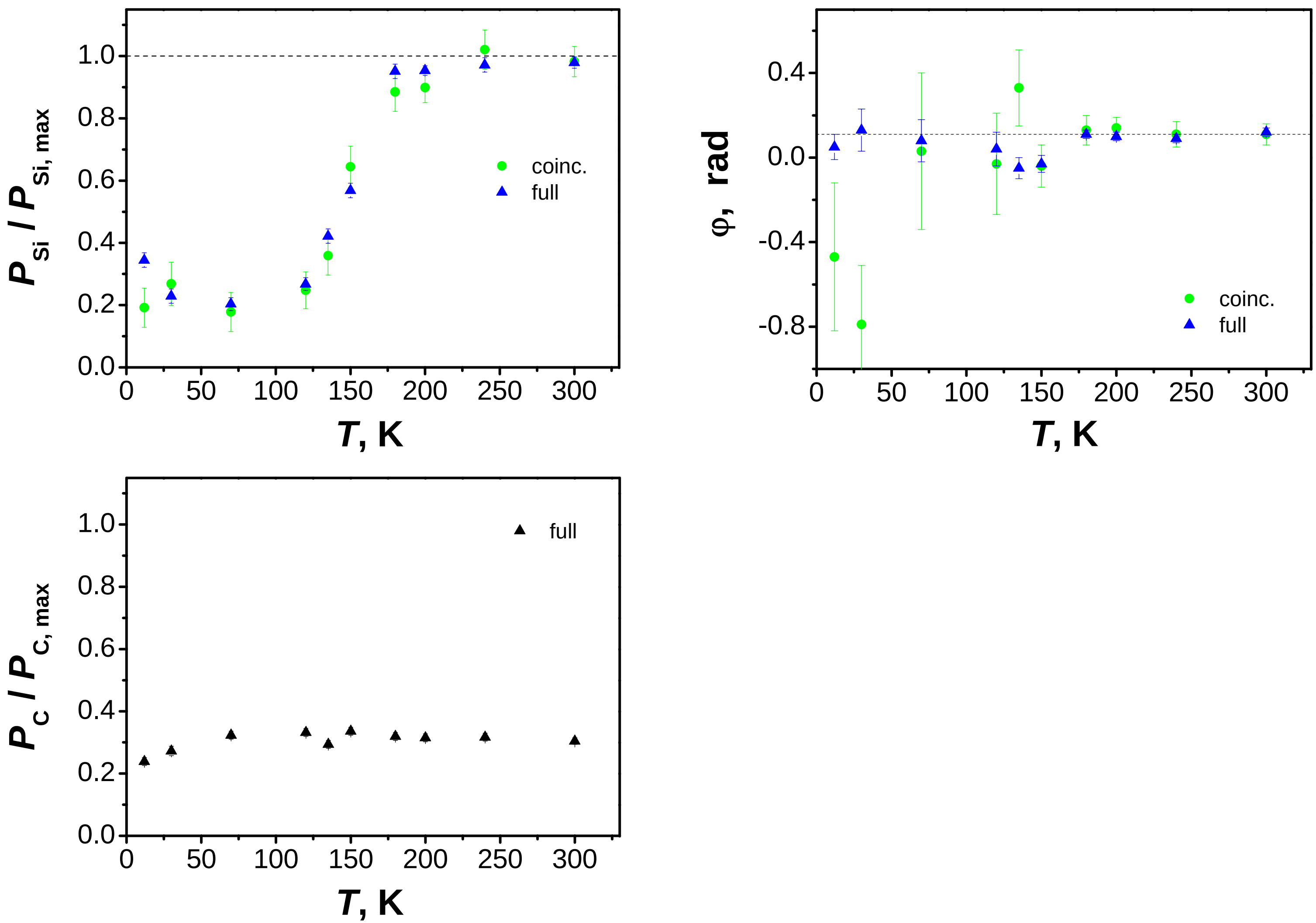
*Suppression of C-component in **coinc.** spectrum -- 20 times*

Fit: 1) Si, C (RT): ω_{Si}(Si) = 84.90(2) rad/μs, ω_C(C) = 85.102(8) rad/μs

2) SiC (coinc.): $\lambda_{Si} \approx 0$

3) SiC (full): a) $\lambda_{Si} = 0$: $\lambda_c \approx 0$, ω_{Si}(SiC) ≈ ω_{Si}(Si) (10^{-3}), ω_c(SiC) ≈ ω_c(C) ($7\cdot10^{-4}$)

b) $\lambda_{Si} = 0$, $\lambda_c = 0$, ω_{Si}(SiC) = ω_{Si}(Si), ω_c(SiC) = ω_c(C)



Model:

hydrogen like atom: $S_{\mathrm{h}} = 1/2$

high field limit: $\omega_{\mathrm{h}} = g_{\mathrm{h}}\mu_{\mathrm{B}}H/\hbar \sim$ 2800 MHz $\gg \Omega$

Ω – frequency of the hyperfine interaction;

ω_0 – free muon-spin frequency.

$$\frac{d}{dt}P_0 = i\omega_0 P_0 + \nu\left(P_1 + P_2\right)$$

$$\frac{d}{dt}P_1 = \left(i\omega_1 - \nu\right)P_1$$

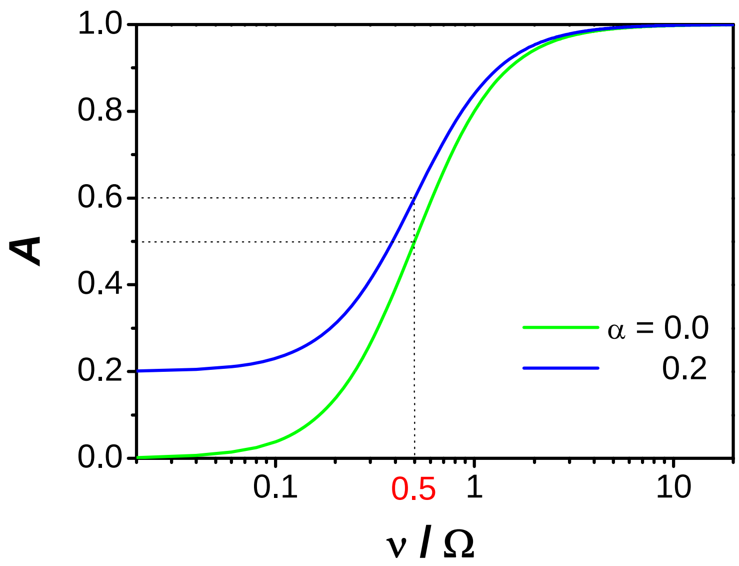
$$\frac{d}{dt}P_2 = \left(i\omega_2 - \nu\right)P_2$$

$\omega_1 = \omega_0 - \Omega/2$ $\qquad P_0(0) = \alpha$

$\omega_2 = \omega_0 + \Omega/2$ $\qquad P_1(0) = P_2(0) = (1-\alpha)/2$

$$A = \alpha + \frac{1-\alpha}{1 + \left(\frac{\Omega}{2\nu}\right)^2}\ ; \qquad \phi = 0$$

$$P_0 = \underline{A\, e^{i\omega_0 t + \phi}} + \underline{\sum_{\mathrm{k}=1}^{2} C_{\mathrm{k}} e^{i(\omega_{\mathrm{k}} - \nu)t}}$$



observed signal

not observed at $\Omega/2\pi \geq 500$ MHz

Thermal ionization of μAl acceptor

$$\nu = N_{\rm v}\,\sigma\,v_{\rm th}\,e^{-E_{\rm i}/kT}$$

$N_{\rm v}$ – the density of states in the valence band;
σ – the cross section for hole capture by a negatively charged acceptor;
$v_{\rm th}$ – the thermal velocity of holes;
$E_{\rm i}$ – the acceptor ionization energy.

$$N_{\rm v} = 4.9\cdot 10^{15}\;T^{3/2}$$
$$v_{\rm th} = 6.7\cdot 10^{5}\;T^{1/2}$$

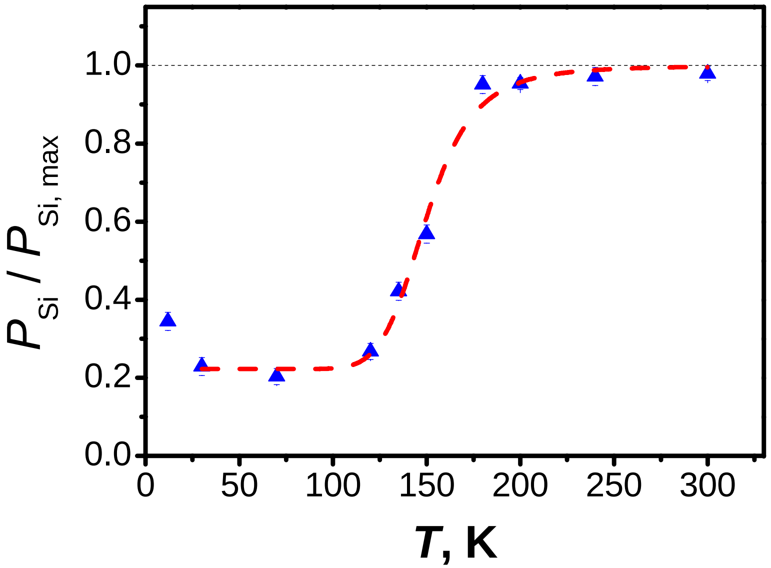
at $m_{\rm h}^{*} = m_{\rm e}$

$$\sigma = \sigma_{100\,\rm K}\cdot 10^{6}\;T^{-3}, \quad \text{i.e } \sigma\sim T^{-3} \qquad [1]$$

[1] V.N. Abakumov *et.al*, Sov.Phys.Semicond. **12**, 1 (1978)

$$\nu = 3.3\cdot 10^{27}\;\sigma_{100\,\rm K}\;T^{-1}\;e^{-E_{\rm i}/k_{\rm B}T}$$

$$\frac{P_{\rm Si}}{P_{\rm Si,max}} \equiv A = \alpha + \frac{1-\alpha}{1+\left(\frac{\Omega}{2\nu}\right)^2}$$



At $\Omega/2\pi = 500$ MHz

$$\alpha = 0.22 \pm 0.01$$
$$\sigma_{100\,\rm K} = (6.5\pm 3.4)\cdot 10^{-14}\ {\rm cm}^2$$
$$E_{\rm i} = (88\pm 7)\ {\rm meV}$$

Al-acceptor:
$E_{\rm i} \approx 240$ meV

Ionization of μAl by electron capture

$$\nu = n_e \, \sigma \, v_{th}$$

n_e – concentration of electrons in the conduction band;
σ – cross section for electron capture
by a neutral $_\mu$Al acceptor;
v_{th} – thermal velocity of electrons.

$$n_e \approx \frac{1}{\sqrt{2}} \, (N_d \cdot N_c)^{1/2} \; e^{-E_d/2\,k_B T}$$

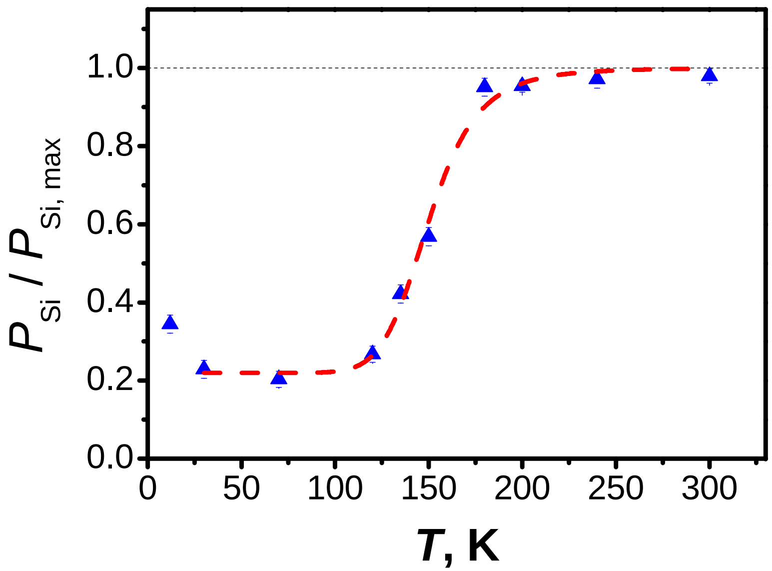
N_d – concentration of donor impurities;
N_c – density of states in the conduction band;
E_d – donor ionization energy.

$$N_c \approx 3.25 \cdot 10^{15} \; T^{3/2}$$

$$v_{th} \approx 1.1 \cdot 10^{6} \; T^{1/2}$$

$$\nu = 4.4 \cdot 10^{13} \; (\sigma \, N_d^{1/2}) \; T^{5/4} \; e^{-E_d/2\,k_B T}$$

$$\frac{P_{Si}}{P_{Si,max}} \equiv A = \alpha + \frac{1-\alpha}{1+\left(\frac{\Omega}{2\nu}\right)^2}$$



$$\alpha = 0.22 \pm 0.01$$

$$\sigma \, N_d^{1/2} = (5.9 \pm 2.9) \cdot 10^{-6} \; \mathrm{cm}^{1/2}, \; \text{at} \;\; \Omega/2\pi = 500 \; \mathrm{MHz}$$

$$E_d = (115 \pm 13) \; \mathrm{meV}$$

N-donor: $E_d = (50 - 150)$ meV