WINTER SCHOOL 2006, REPINO

The effect of uniaxial stress on the behavior of aluminum acceptor impurity in silicon

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Motivation.

I. As well known, the usage of semiconductors in modern electronics is based on:

a) the possibility to change the concentration of free charge carriers in semiconductors by changing the concentration of acceptor and/or donor impurities;

b) and on the possibility to control the charge transport process in semiconductor by applying external electric (and/or magnetic) field.

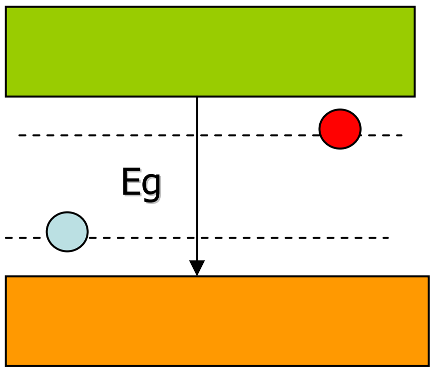
II. At present theory and experiment study the possibility of building new basic elements of electronics based on the following properties of impurity centers and free charge carriers in semiconductors:

a) free charge carriers have spin, they can be polarized and thus transport of spin polarized charge could be provided in semiconductor (spin polarized transport, spintronic);

b) acceptor and donor impurity atoms have nonzero magnetic moment at temperatures below a few tens Kelvin degree and they may be polarized. Moreover, most of impurity atoms have nuclear magnetic moment, and at low temperatures hyperfine interaction between magnetic moments of nucleus and atomic electron takes place.

This idea could be realized by using hetorostructured semiconductors. The spin relaxation of charge carriers and of impurity centers are the critical parameters for this implementation. As known, in heterostuctures the semiconductor is strained in direction normal to the basic plane. Therefore, it is necessary to study relaxation of impurity centers in uniaxially strained semiconductor, as well as to study the relaxation of acceptor centers in uniaxially stressed silicon.

Muonic atom is a shallow acceptor impurity in semiconductors



B	C	N
Al	Si	P
Ga	Ge	As

ns^2np^1 ns^2np^2 ns^2np^3

Al^{-1} – ionized, diamagnetic
Al^0 – neutral, paramagnetic

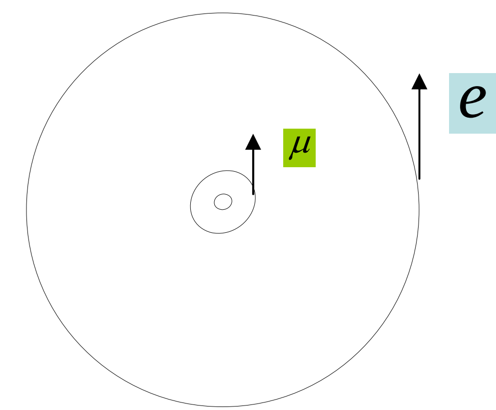
The impurity of N, P and As in silicon is a donor center

The impurity of B, Al and Ga in silicon is a shallow acceptor center (AC)

Capture of a negative muon by host atom in silicon results in formation of muonic atom which imitates aluminum atom

$r_B(e)/r_B(\mu) \approx m_\mu / m_e \approx 207$

- $Si + \mu^- \longrightarrow {}_{\mu}Al$

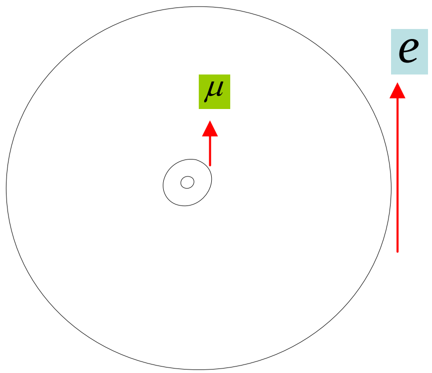


What one can observe in μSR experiments in semiconductors?

- When the $_\mu$Al acceptor center is formed in the paramagnetic state $_\mu Al^0$, the electron shell of the muonic atom has nonzero magnetic moment. In this case, the behavior of the muon polarization is determined by the hyperfine interaction between the magnetic moments of the muon and electron shell of the $_\mu Al^0$ atom and by interaction between the electron shell of $_\mu Al^0$ and its environment. The relaxation of electron shell of AC can be caused by scattering of charge carriers on an acceptor and by interaction of acceptor center with the crystal lattice.

- According to V.N. Gorelkin et al. (Physica B 289, 585 (2002)), at $\nu \gg A_{hf}$ there are analytical relations between time evolution of muon polarization in 1S state with hyperfine interaction constant A_{hf} and the relaxation rate ν of magnetic moment of the $_\mu Al^0$ acceptor:

$$\frac{\Delta\omega}{\omega_d} = \frac{\omega_p - \omega_d}{\omega_d} = \frac{g\mu_B}{2\mu_B^\mu} \cdot \frac{J(J+1)A_{hf}}{3k_B T}$$



$$\lambda = \frac{J(J+1)}{3}\left[\frac{(A_{hf}/\eta)^2}{\nu} + \frac{(A_{hf}/\eta)^2 \nu}{\nu^2 + \omega_e^2}\right]$$

$$\nu = C \cdot T^{\alpha}$$

For uniaxial compression of the silicon samples beryllium-bronze pressure cell was constructed. The cell provides pressure up to 5 kbar to the sample

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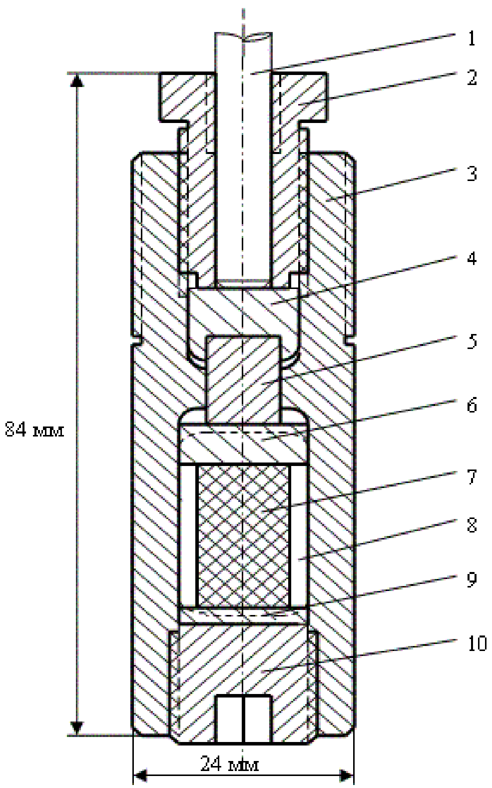
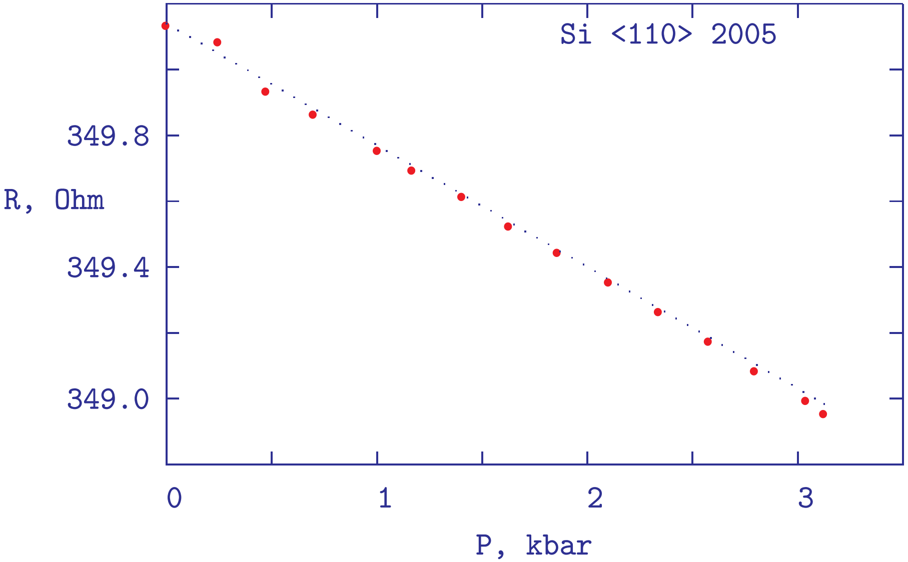
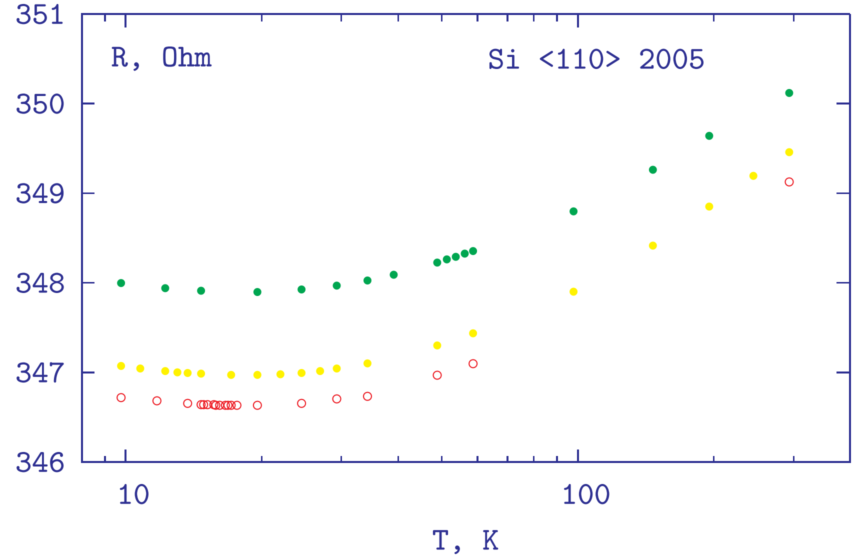
Instruments and Experimental Techniques **48**, 535 (2005)



1 – rod	4 – pressure bearing	7 – sample
2 – fixing screw	5 – plunger	8 – window
3 – cell body	6,9 – sample bearing	10 – bearing screw

Pressure on sample is controlled by gauge (resistance) sensor



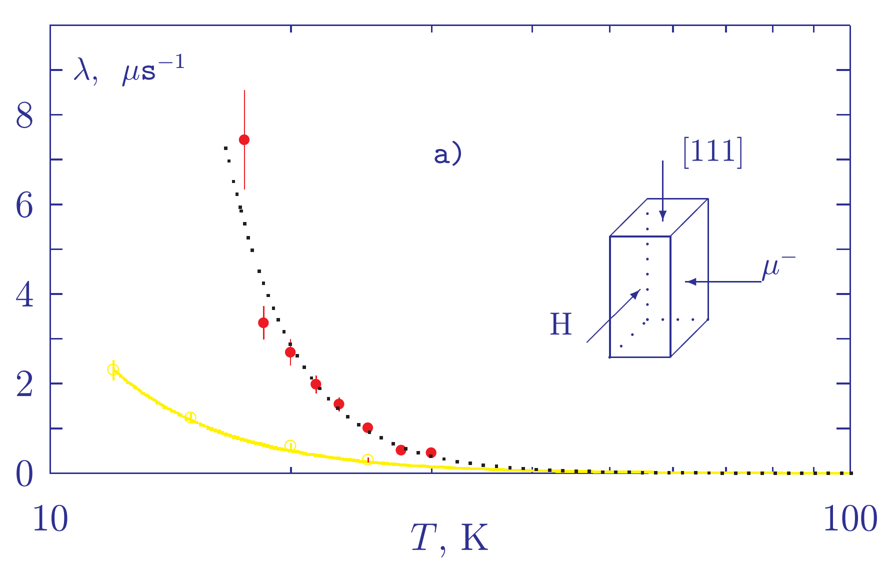


- Dependence of the resistance of gauge sensor on external pressure on Si sample at 300 K (left)
- Temperature dependence of the resistance of gauge sensor at pressure 0, 2.13 and 2.9 kbar on silicon sample (right)

Samples: Czochralski (Cz) and float-zone (FZ) grown single crystal silicon

sample	ρ, Ohm.cm	Stress direction	field orientation	Sample dimension
Si-1 , (Cz)	266	*P* ||<111>	H || $<1\bar{1}0>$	22x9.5x9.5 mm
Si-2 , (Cz)	224	*P* ||<100>	H ||<001>	22x9.5x9.5 mm
Si-3 , (FZ)	2000	*P* ||<100>	H ||<001>	22x9.5x9.5 mm
Si-4, (FZ)	2000	*P* ||<110>	H||$<1\bar{1}\sqrt{2}>$	22x9.5x9.5 mm
Si-4 , (FZ)	2000	*P* ||<110>	H ||<001>	22x9.5x9.5 mm

Si:P   [P]=$1.6 \cdot 10^{13}$ cm^{-3} ; P =3 kbar   H||<1$\bar{1}$0>



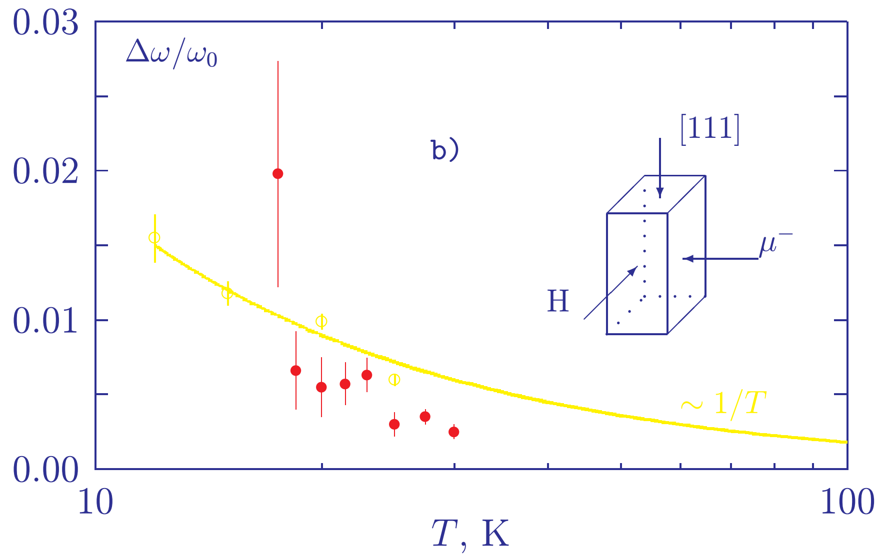
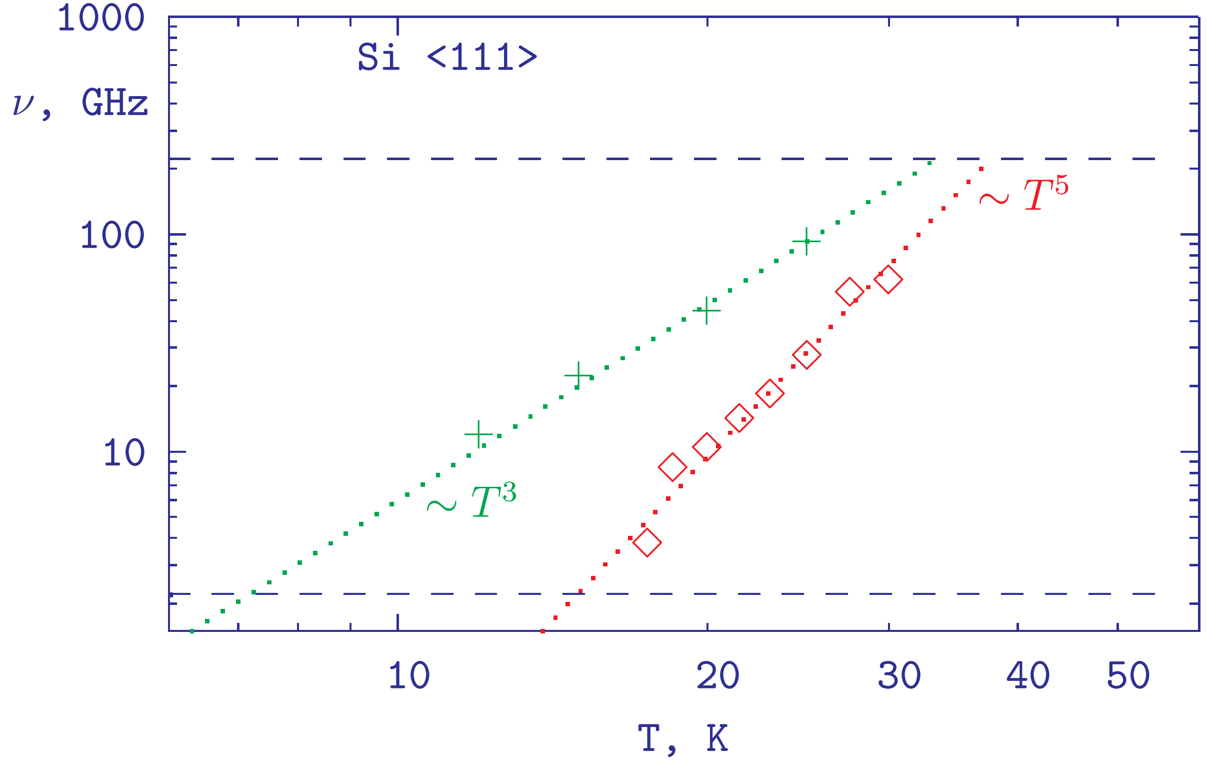


Figure 1. Temperature dependence of the relaxation rate (a) and the frequency shift (b) of the muon spin precession in the silicon sample Si-1. Closed circles correspond to the pressure 3.0 kbar on the sample; opened circles correspond to the absence of pressure. The curves show the results of fit.

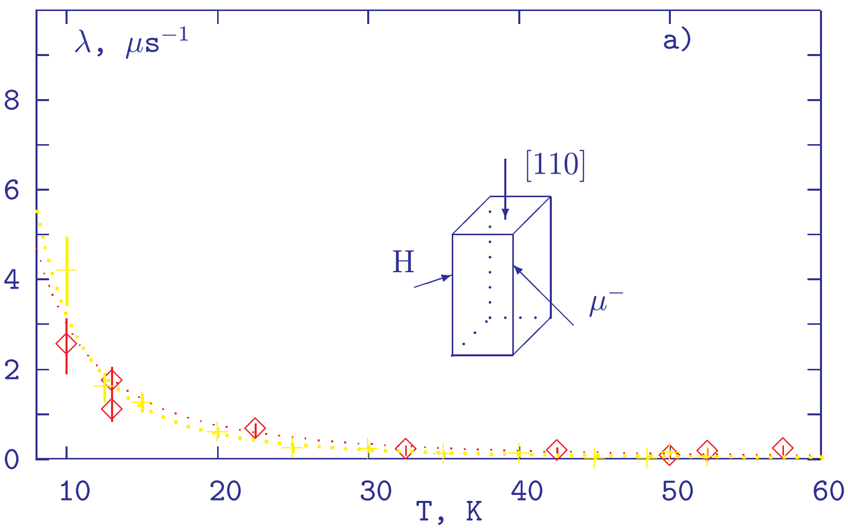
Temperature dependence of the relaxation rate of Al acceptor center in the silicon sample Si-1. Diamond corresponds to the pressure 3.0 kbar on the sample, crosses correspond to the absence of pressure

$$\lambda = \frac{J(J+1)}{3}\left[\frac{(A_{hf}/\eta)^2}{\nu} + \frac{(A_{hf}/\eta)^2 \nu}{\nu^2 + \omega_e^2}\right]$$

$$\nu = C \cdot T^{\alpha}$$



Si : P for H||[1Ī√2] and pressure 1.34 kbar



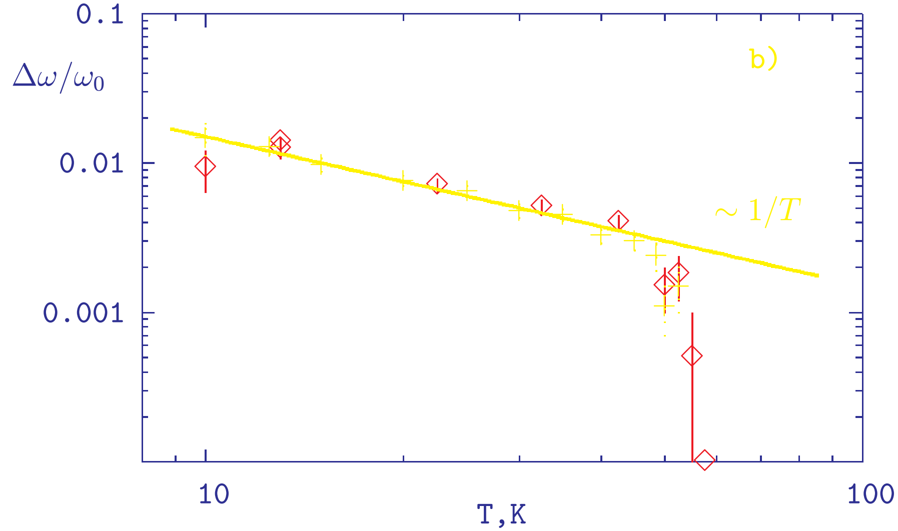


Figure 5. Temperature dependence of the relaxation rate (a) and the frequency shift (b) of the muon spin precession in the silicon sample Si-4 (H□ [1Ī √2]). (+) is for 1.34 kbar pressure on the sample, (◇) is for no external pressure.

Si:P [P]=1.9·10^{13} cm^{-3} ; *P* =1.7 kbar ; H||<001>

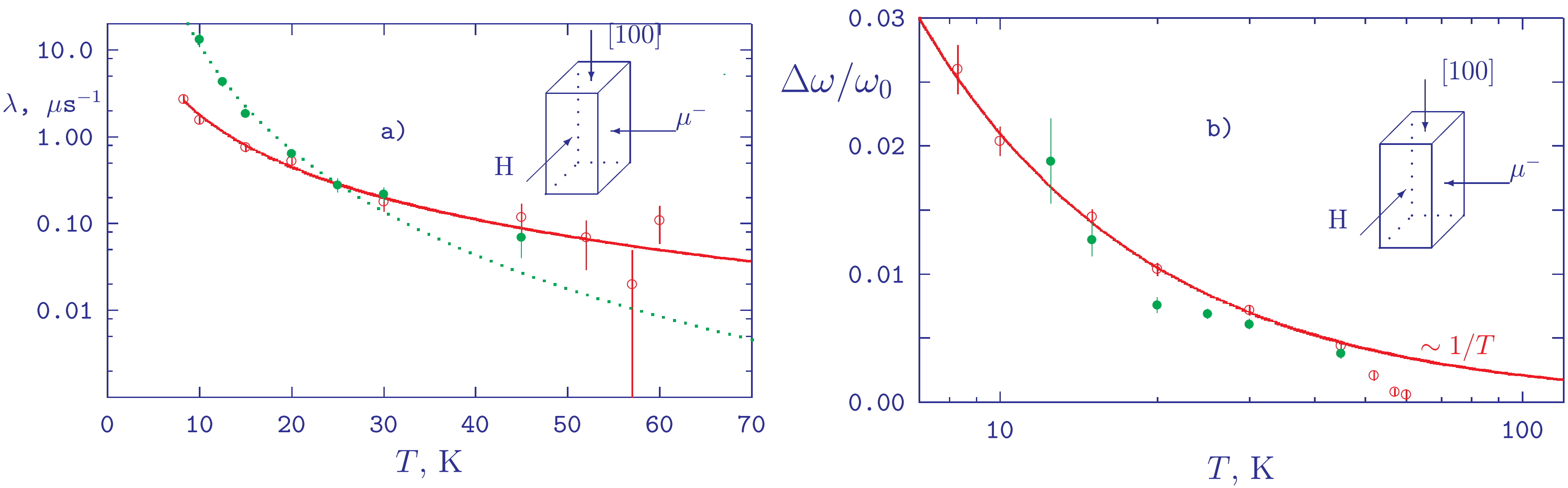


Figure 2. Temperature dependence of the relaxation rate (a) and the frequency shift (b) of the muon spin precession in the silicon sample Si-2. Closed circles correspond to the pressure 1.7 kbar on the sample, opened circles correspond to the absence of pressure. The curves show the results of fit.

Si:P H||<001>

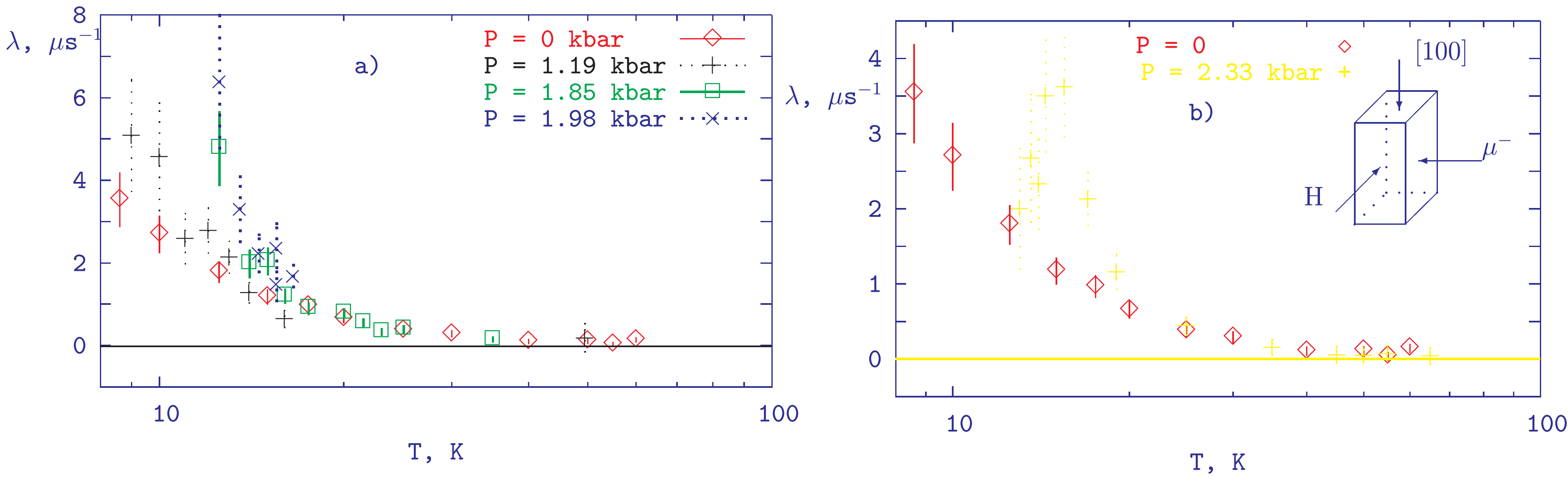


Figure 3. Temperature dependence of the muon spin relaxation rate in the sample Si-3 for different pressures applied along axis [100].

Si:P P = 2.33 kbar ; H||<001>

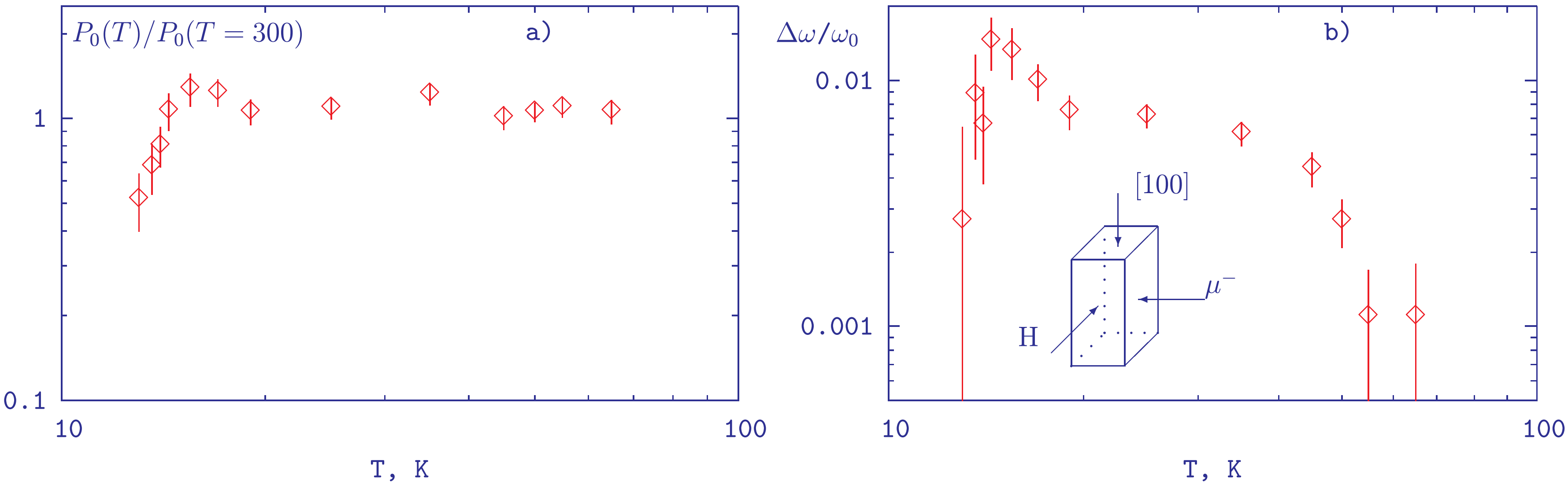
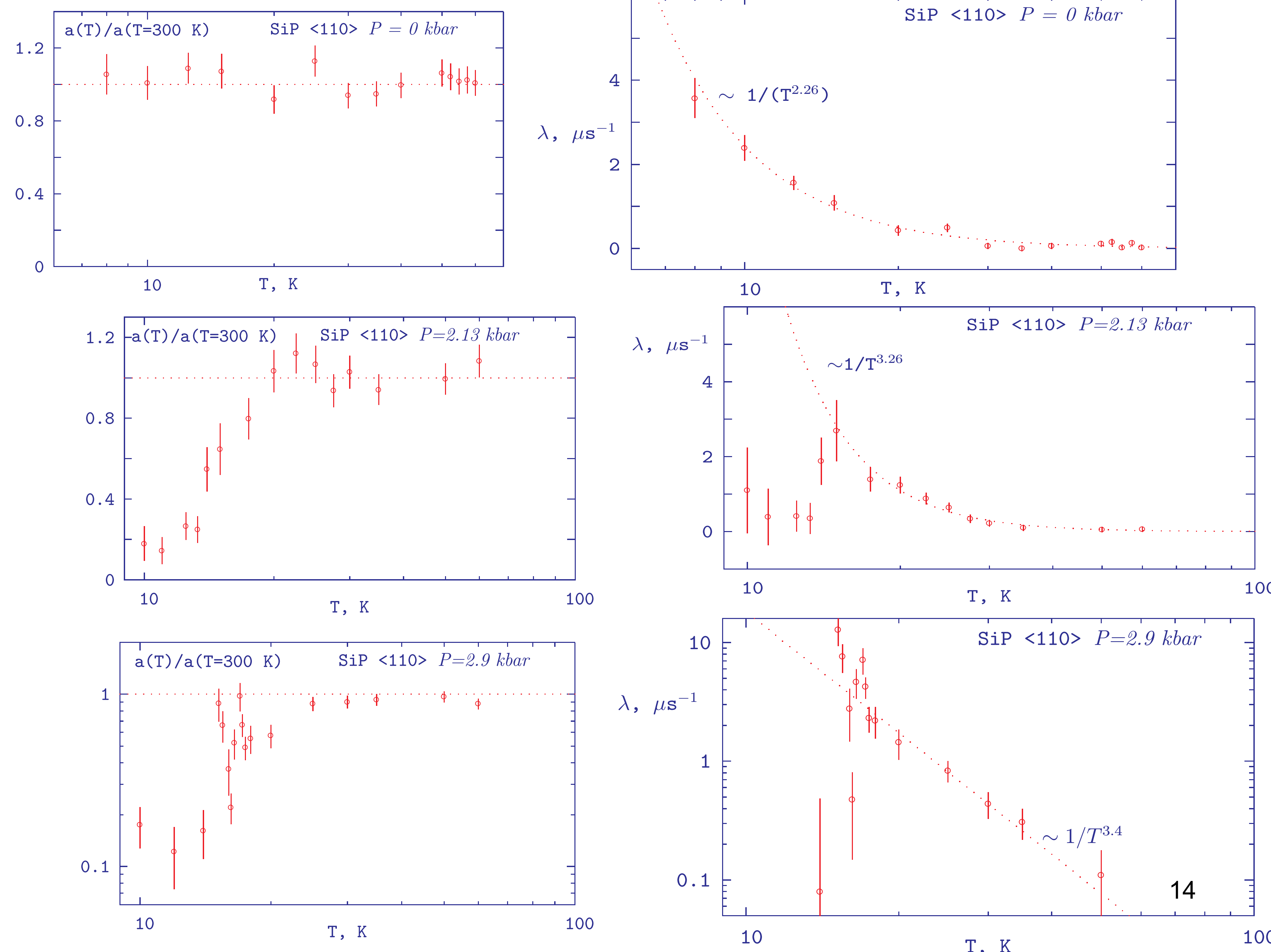
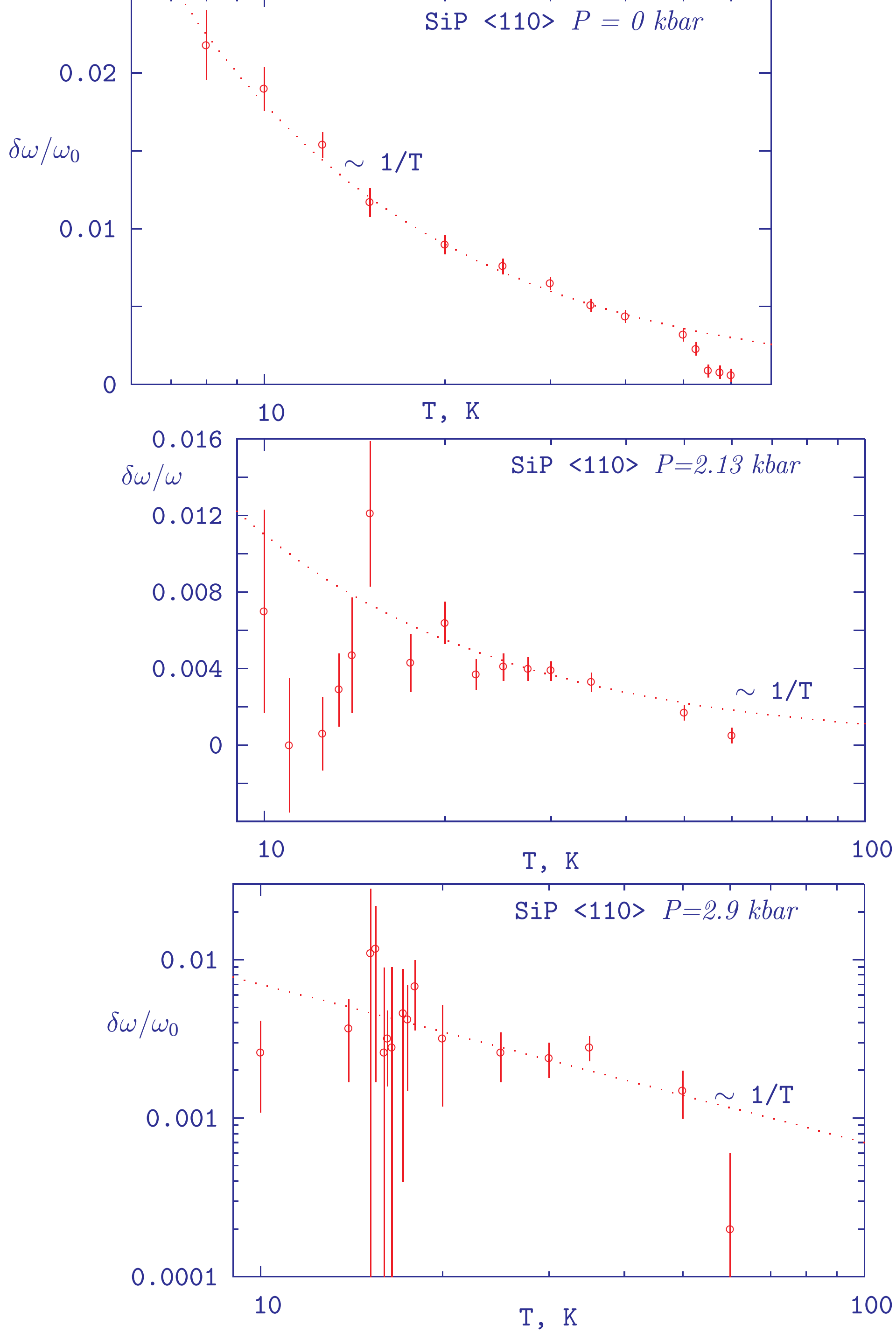
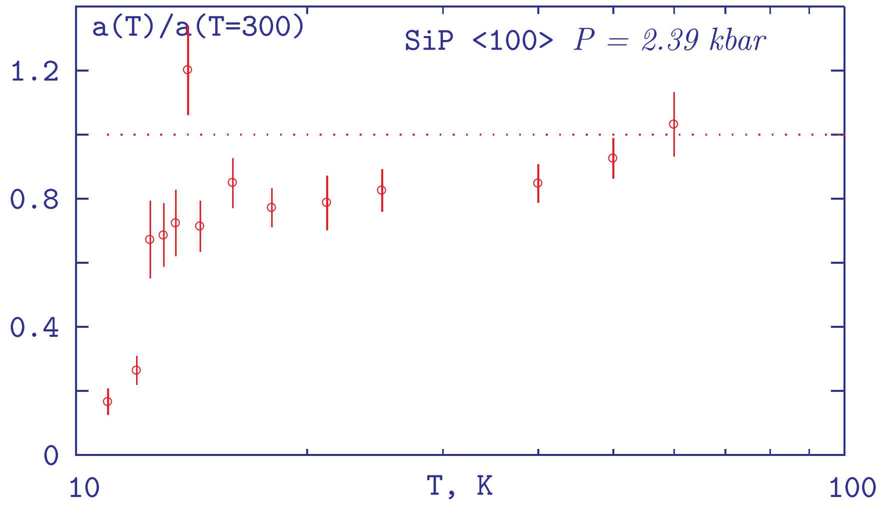


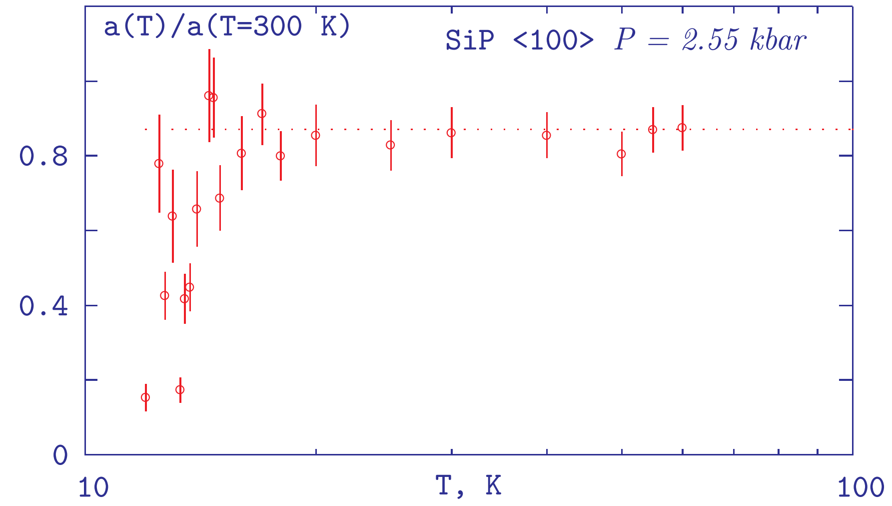
Figure 4. Temperature dependence of the muon spin polarization (a) and the frequency shift of muon spin precession (b) in the sample Si-3 for pressure of 2.33 kbar.


a(T)/a(T=300 K)
SiP <110> P = 0 kbar
T, K
λ, μs^−1
SiP <110> P = 0 kbar
∼ 1/(T^2.26)
T, K
a(T)/a(T=300 K)
SiP <110> P=2.13 kbar
T, K
λ, μs^−1
SiP <110> P=2.13 kbar
∼1/T^3.26
T, K
a(T)/a(T=300 K)
SiP <110> P=2.9 kbar
T, K
λ, μs^−1
SiP <110> P=2.9 kbar
∼ 1/T^3.4
T, K

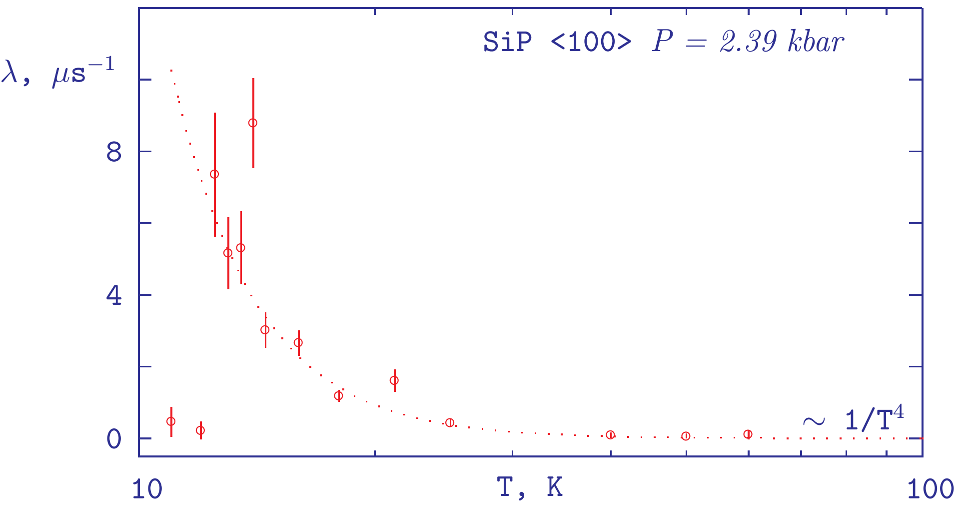

SiP <110> P = 0 kbar
0.02
0.01
0
$\delta\omega/\omega_0$
~ 1/T
10
T, K
SiP <110> P=2.13 kbar
0.016
0.012
0.008
0.004
0
$\delta\omega/\omega$
~ 1/T
10
100
T, K
SiP <110> P=2.9 kbar
0.01
0.001
0.0001
$\delta\omega/\omega_0$
~ 1/T
10
100
T, K



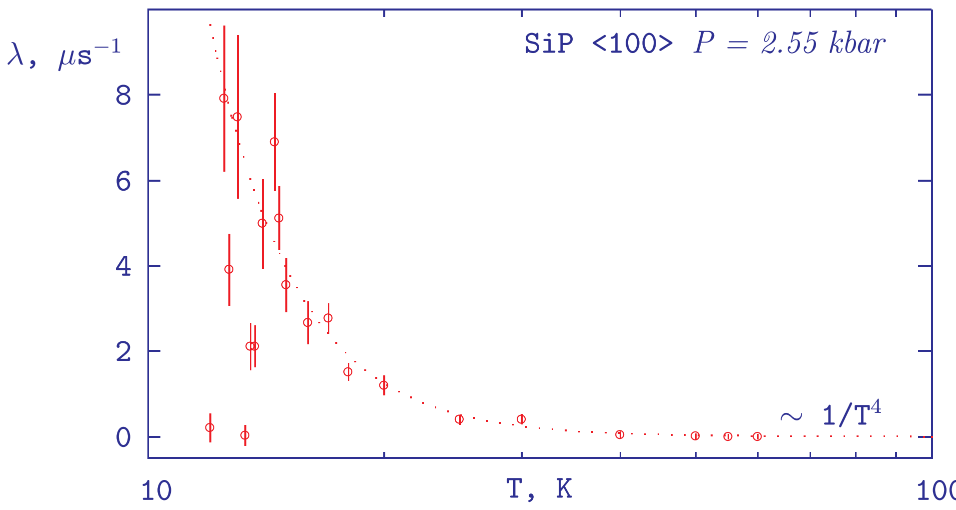
a(T)/a(T=300)
SiP <100> P = 2.39 kbar
1.2
0.8
0.4
0
10
T, K
100



a(T)/a(T=300 K)
SiP <100> P = 2.55 kbar
0.8
0.4
0
10
T, K
100



λ, μs⁻¹
SiP <100> P = 2.39 kbar
8
4
0
∼ 1/T⁴
10
T, K
100



λ, μs⁻¹
SiP <100> P = 2.55 kbar
8
6
4
2
0
∼ 1/T⁴
10
T, K
100

$$\lambda = \frac{J(J+1)}{3}\left[\frac{(A_{hf}/\eta)^2}{\nu} + \frac{(A_{hf}/\eta)^2 \nu}{\nu^2 + \omega_e^2}\right]$$

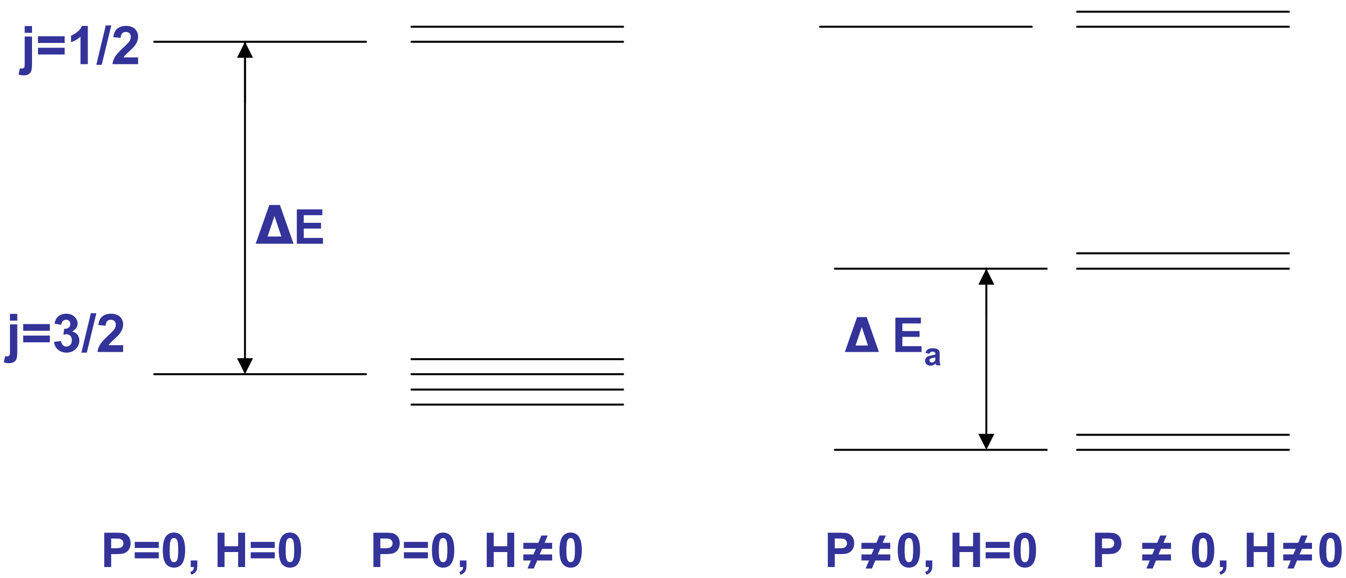
$$\nu = C \cdot T^{\alpha}$$

Sample	ρ, Ohm.cm	Crystal orientation	Field orientation	*P*, *kbar*	C, μs^{-1}	α
Si-1	266	*P* ||<111>	H || <1$\bar{1}$0>	0.0	4.4±2.6	2.7±0.2
				3.0	0.02±0.01	4.8±0.3
Si-2	224	*P* ||<100>	H ||<001>	0.0	60±20	2.0±0.1
				1.7	0.15±0.08	3.8±0.2
Si-3	2000	*P* ||<100>	H ||<001>	0.0	27±11	2.1±0.15
				1.19	0.2−1.8	3.7±0.6
				1.85	0.2−1.8	3.2±0.3
				1.98	<0.17	4.2±1.2
				2.33	<0.1	4.1±0.6
				3.39		~4
				2.55		~4
Si-4	2000	*P* ||<110>	H||<1$\bar{1}\sqrt{2}$>	0.0	39±26	2.0±0.24
				1.34	6.5±4.0	2.6±0.20
Si-4	2000	*P* ||<110>	H ||<001>	0.0	2.1±1.0	2.26±0.16
				2.13		3.27±0.24
				2.9		~3.4

Splitting of the ground state of acceptor center in stressed silicon decreases the relaxation rate of AC

in diamond Δ(B) = 2 meV Physica B, 273, 640 (1999)

- in silicon Δ (Al) = 18.5 meV Phys.Rev. B, 57, 15315 (1998); 62, 8080(2000)



- ΔE_a [meV]= 2·P[kbar] ; $k_B T$=2 meV at T=23 K
- $\mu_B H$[kOe] = $0.58 \cdot 10^{-2}$ meV

The relaxation rate of acceptor center in silicon: theoretical study

Mechanismis of relaxation AC: 1) scattering charge carriers on AC,

2) interaction of AC with phonon.

- **V.G.Nosov, I.V.Yakovleva, Zh.Exp.Teor.Fiz., 43, 1750(1962)**

$$\nu \approx \sigma \cdot N_{e(h)} \cdot \sqrt{\frac{2T}{\pi \cdot m^*}} \qquad N_{e(h)} = N_0 \cdot e^{-E_i/T}$$

$$\sigma \approx 4 \cdot \pi \cdot a_B^2$$

- **Y.Yafet //J. of Phys. Chem. Solids, 26, 647(1965).**
  - **a) one phonon process: ν~T (T< 1 K)**
  - **b) Raman scattering of phonons: ν ~T^5 (10< T <100 K)**
  - **c) Orbach process: ν ~ $e^{-\Delta T}$ (negligible below 100 K)**

- **T.Shimizi, M.Nakayama //J. of Physical Society of Japan, 19, n.10, 1829(1964).**

$$\nu \propto T^9 \qquad \textbf{2<T<10 K}$$

Summary

- The relaxation rate of the aluminum acceptor center in silicon and its temperature dependence are very sensitive to the crystal orientation in the magnetic field

- Uniaxial stress of silicon alters the relaxation rate and its temperature dependence

- The effect of the compression on the AC relaxation depends on the direction of the stress relative to the crystallographic axes of silicon

I am grateful to PSI Directorate for the possibility to carry out this experiment at PSI

THE END