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Illumination effects in irradiated 6H n-type SiC observed by positron annihilation spectroscopy

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Abstract

In the presented study, we used positron annihilation spectroscopy to investigate defects after electron irradiation in 6H n-type SiC. The density of vacancy-type defects strongly increased during this treatment. An isochronal annealing experiment was performed, and the main recovery stage was found to be between 1000°C and 1400°C. This corresponds to the annealing range of the E1/E2 defect, which was also found by a correlated positron and DLTS study in 6H-SiC epilayers after electron irradiation [1]. Optical excitation experiments during the positron experiment show that the observed defect has an ionisation level at about E_c-0.47 eV, which is similar to the level E_c-0.44 eV obtained by DLTS for the E1/E2 defect [2]. Doppler-coincidence experiments suggest that the observed vacancy is surrounded by C atoms, so that most probably the Si vacancy (isolated or bound to an impurity or another defect) is the dominating defect after electron irradiation.

Key Words: SiC, Annealing, Radiation Defect, Positron Annihilation

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1. Introduction

Electrical and optical properties of defects in semiconductors play an important role in SiC based wide band gap electronic devices. One way to introduce defined defects in SiC is the electron irradiation. Irradiated SiC was studied by several experimental methods to characterize the introduced defects (DLTS, PL, ESR). In order to study open-volume defects we performed positron lifetime experiments for n-type 6H SiC irradiated with 2 MeV electrons (dose: 1×10^{17} cm^{-2} and 3×10^{17} cm^{-2}). The positron lifetime was found to increase after irradiation indicating the presence of vacancy-type defects. Annealing experiments were performed to observe the disappearing or agglomeration of vacancies. The excitation of electrons to the conduction band due to illumination shows different annealing behavior dependent on the irradiation dose. Additional coincidence Doppler broadening experiments were performed to get information about the chemical environment of vacancies observed by positrons.

2. Experimental details

N-doped SiC bulk wafers ([N]= $1\times10^{17}cm^{-3}$) of a thickness of 0.3 mm were purchased by Nippon Steel Company and irradiated in Japan Atomic Energy Research Institute (JAERI) with 2 MeV electrons for two different doses (1×10^{17} cm^{-2} and 3×10^{17} cm^{-2}) at room temperature. The size of the samples is 5 x 5 mm^2. A conventional positron emitter $^{22}NaCl$ (10-90 µCi) was used as positron source. It was encapsulated with 4 µm of aluminum foil. Due to the high kinetic energy of positrons (E_{max} = 0.54 MeV) 2 % of them get through the thin samples. To prevent the annihilation of positrons in the sample holder, an additional piece of SiC was arranged on both sides of the sandwich. The positron lifetime measurements were performed with a conventional fast-fast positron lifetime spectrometer (FWHM=260 ps) in the temperature range of 15 K to 600 K. The illumination experiment using an optical cryostat was carried out in the same temperature range. The effect of illumination on positron lifetime was examined using white and monochromatic light (hν = 0.3–3.2 eV). In the range between 100°C and 1300°C the samples were annealed in a furnace under vacuum and up to 1700°C under ambient argon atmosphere to avoid the sublimation of silicon from the surface. Doppler broadening coincidence experiments were performed using two Ge-detectors with a resulting resolution function of about 1 keV.

3. Results and Discussion

Figure 1 shows the difference of the average lifetime of low-dose electron irradiated 6H SiC (dose: 1×10^{17} cm^{-2}) with monochromatic light and in darkness as a function of photon energy. The direct transition of electrons from the valence band to the conduction band causes the disappearance of the illumination effect above a photon energy of 3 eV. It is found that the average lifetime increases from 0.4 eV and tend to saturate above 1 eV. This could be explained as the internal transition of electrons from localized levels to the conduction band (fundamental absorption). The lower threshold energy for the appearance of the illumination effect is associated with the position of the energy level of defects in the band gap acting as a trapping center for positrons. According to the Lucowsky model [7] the threshold energy is determined to be E = 0.47 eV from the fitting as shown in Fig.1. DLTS studies showed that the energy level of E_1/E_2 is located at 0.35-0.44 eV below the conduction band [2,6]. Concerning an indirect transition from the ground state to the conduction band [2] the small difference of these two energies allows us to conclude that the observed threshold energy (0.47 eV) might be related to the E_1/E_2 level.

Figure 2 shows the isochronal annealing behavior of average positron lifetime in darkness measured at 20 K. From this figure, two annealing steps are seen: The first is from room temperature to 250°C and the second is above 1000°C. The first step can be explained as the recombination of Frenkel pairs and the annealing of carbon vacancies, which are mobile below 300°C. Considering that pure silicon vacancies are mobile at 600-800°C [5], the higher thermal stability of trapping centers can be explained as a creation of complexes involving Si vacancies. This could be concluded due to the nearly constant defect-related lifetime (190±5ps) determined by decomposition of positron lifetime spectra in the range of annealing temperature from 400 to 1200°C. Above 1300°C, all detectable vacancy-type defects disappear [1]. Based on theoretical calculations [3] and a positron lifetime experiment combined with electron spin resonance [4], the lifetime of positrons at silicon vacancies is 187-193 ps. Thus, it seems that the major positron trapping center is related to silicon vacancies. It is important to note that E_1/E_2 defects observed in DLTS experiments also disappear in the same temperature region [6]. Thus, we conclude that the E_1/E_2 center is decorated with a silicon vacancy. The annealing behavior under illumination shows very similar characteristics [8], so that introduced vacancy-type defects due to electron irradiation are responsible for the illumination effect.

Figure 3 presents the annealing characteristics of average positron lifetime for the electron irradiated 6H n-type SiC with a dose of 3×10^{17} cm^{-2} for two different measurement temperatures. For the low-temperature measurements, the annealing characteristics show a very similar behavior in case of illumination and darkness. The effect of illumination slightly decrease due to the annealing temperature. The annealing behavior can be divided into 4 steps. The first step is the recombination of Frenkel pairs, which reduces drastically the average lifetime below 200°C annealing temperature. Then, a bright shoulder follows up to 500°C where carbon vacancies will become mobile and anneal out [1]. The average lifetime increases near 800°C due to the building of complexes with silicon vacancies, and after 1200°C most of introduced vacancy-type defects annealed out. The high-temperature measurements show a completely different annealing behavior. No illumination effect is to be seen up to an annealing temperature of 600°C. Above this temperature, the average lifetime is higher under illumination, which was not observed for the low-temperature measurements. The last picture in figure 3 c) shows the difference of average lifetime under illumination and in darkness. It shows that a small increase of average lifetime appears in the mobility range of the two kind of vacancies.

The decomposition of positron lifetime spectra for the annealing temperature 800°C is displayed in the fourth figure. It demonstrates that for a measurement temperature of 300K two different types of defects act as trapping centers for positrons. Under illumination the defect-related lifetime τ_2 has an value of 190±10ps similar to the silicon vacancy [3]. In darkness, an additional defect (unknown defect with an ionization Energy: E >100meV) act as a trap (τ_2=165±10 ps) in competition with the silicon vacancy. The decomposed lifetime is a mixture of these two defects where the value of positron lifetime for the silicon vacancy approaches for the high measurement temperature. The above mentioned deep center must change their charge state (negative to neutral) due to the excitation of electrons from the deep level to the conduction band.

Figure 5 shows the annealing behavior for the Doppler broadening spectroscopy. The W-parameter is sensitive for the chemical environment of the trapping center. The S-parameter represents the open-volume space and the concentration of open-volume defects. The straight line found during annealing allows us to conclude that only monovacancies anneal out and no additional vacancy type defect is involved [10]. After 1200°C annealing some defects remain which cannot be isolated monovacancies [4]. This indicate that silicon vacancies and complexes with silicon vacancies are the major trapping centers.

4. Conclusions

In summary, we performed positron lifetime measurements with n-type 6H SiC after 2 MeV electron irradiation for two different doses in darkness and under illumination. After the 1300°C annealing, vacancy-type defects and the illumination effect disappear. The annealing behavior in darkness shows very similar behavior to the E_1/E_2 centers observed by DLTS measurements. Thus, we conclude that the observed defect contains silicon vacancies. The determined threshold energy of 0.47 eV for the illumination effect further supports this assumption. In the case of high dose irradiation more than one optical active trapping center was found for the measurement temperature of 300 K. To clarify the structure of possible complexes with silicon vacancies, further experiments are necessary.

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Figure Captions

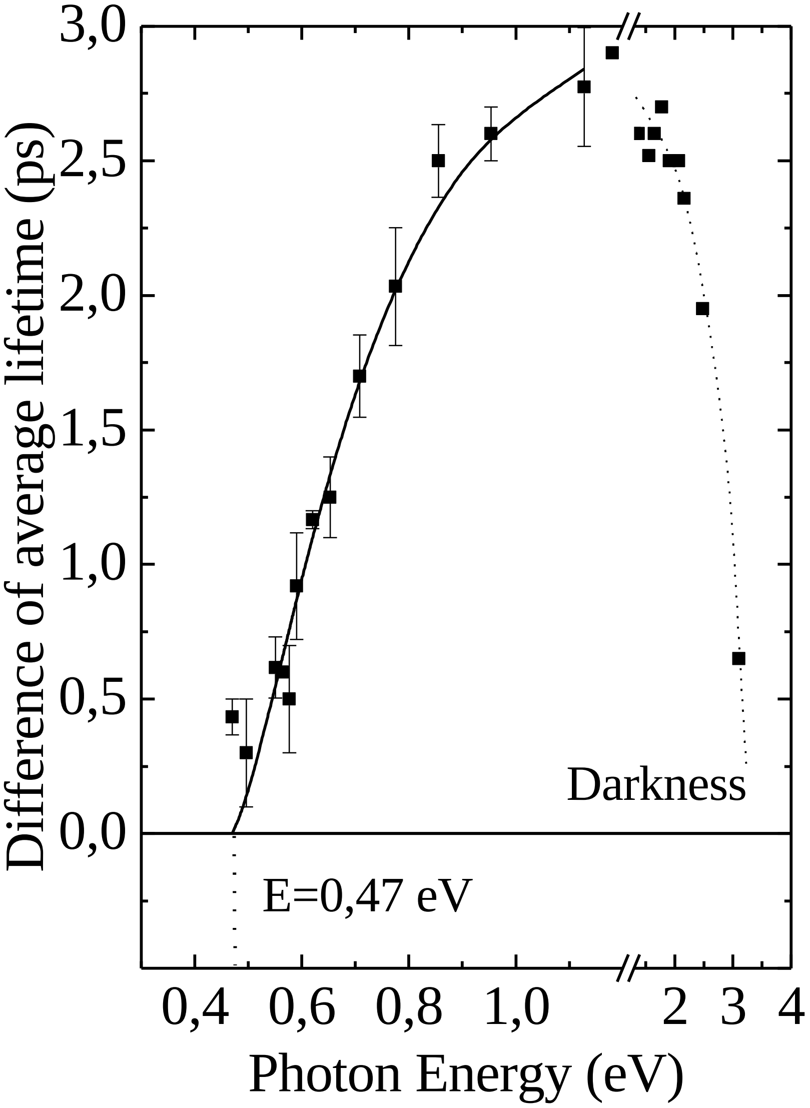
Figure 1
Difference of average positron lifetime under illumination and in darkness as a function of photon energy.

Figure 2
Average positron lifetime as a function of annealing temperature for electron irradiated 6H n-type SiC (dose: 1×10^{17} cm^{-2}).

Figure 3
Average positron lifetime as a function of annealing temperature for electron irradiated 6H n-type SiC (dose: 3×10^{17} cm^{-2}) under illumination and in darkness. The picture c) show the difference of average lifetime between darkness and illumination for the measurement temperature of 20K.

Figure 4
Positron lifetime as a function of measurement temperature for 6H n-type SiC annealed at 800°C (irradiation dose: 3×10^{17} cm^{-2}).

Figure 5
Doppler broadening line-shape parameters S and W of the 511 keV annihilation peak as a function of annealing temperature (irradiation dose: 3×10^{17} cm^{-2}).



3,0
2,5
2,0
1,5
1,0
0,5
0,0
Difference of average lifetime (ps)
Darkness
E=0,47 eV
0,4
0,6
0,8
1,0
2
3
4
Photon Energy (eV)

Figure 1

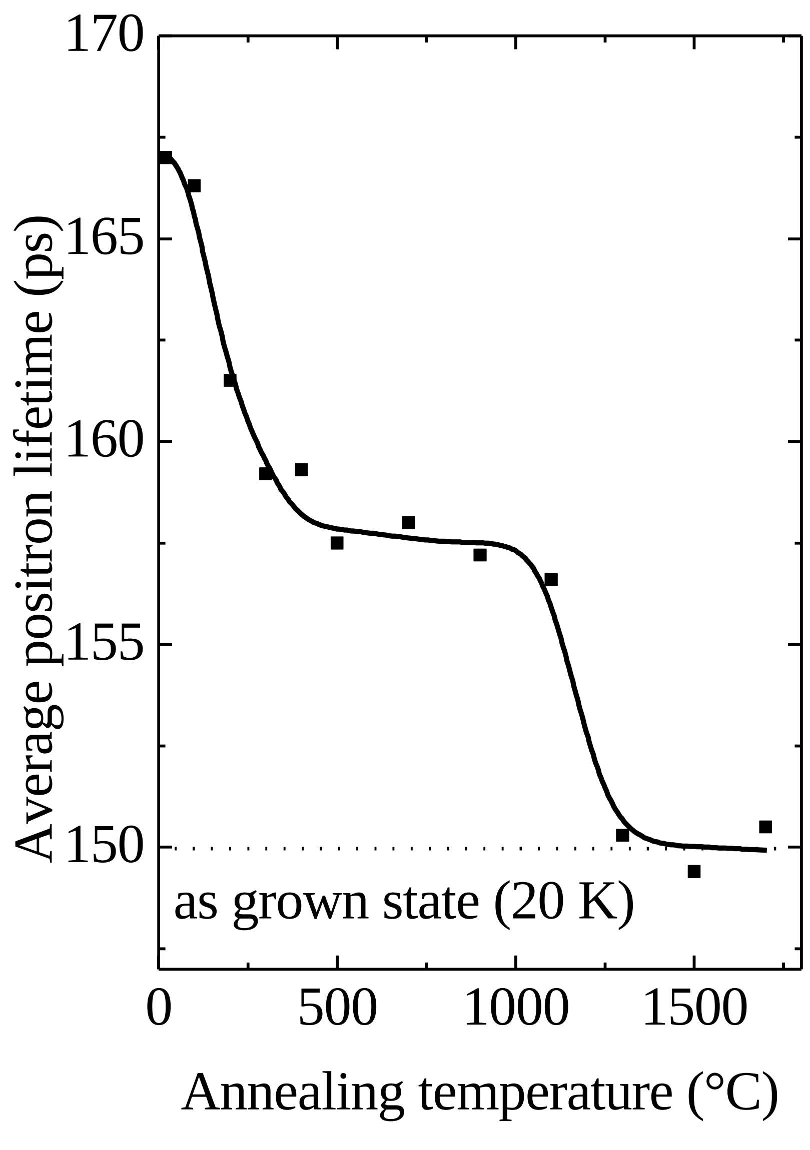
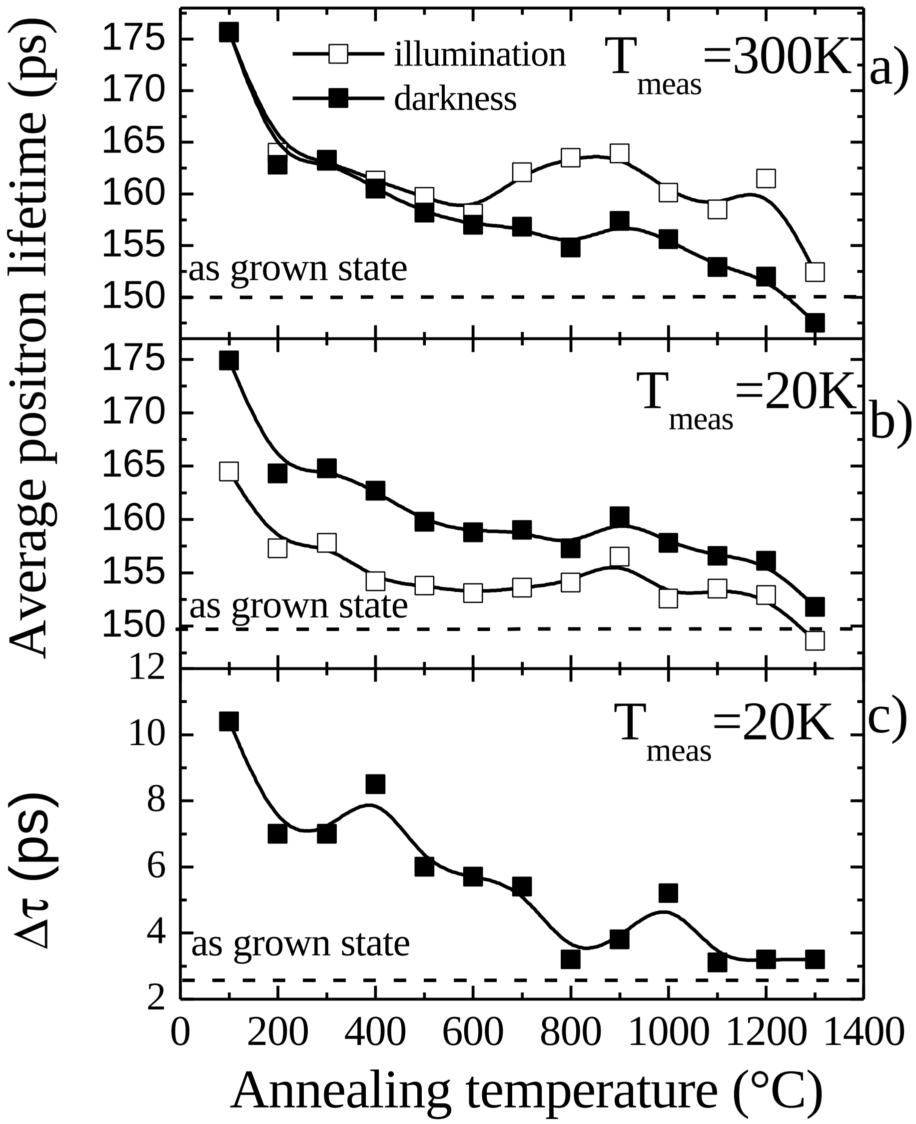

170
165
160
155
150
Average positron lifetime (ps)
as grown state (20 K)
0
500
1000
1500
Annealing temperature (°C)

Figure 2



illumination
darkness
T_meas=300K
a)
T_meas=20K
b)
T_meas=20K
c)
as grown state
as grown state
as grown state
Average positron lifetime (ps)
Δτ (ps)
Annealing temperature (°C)
175
170
165
160
155
150
12
10
8
6
4
2
0
200
400
600
800
1000
1200
1400

Figure3

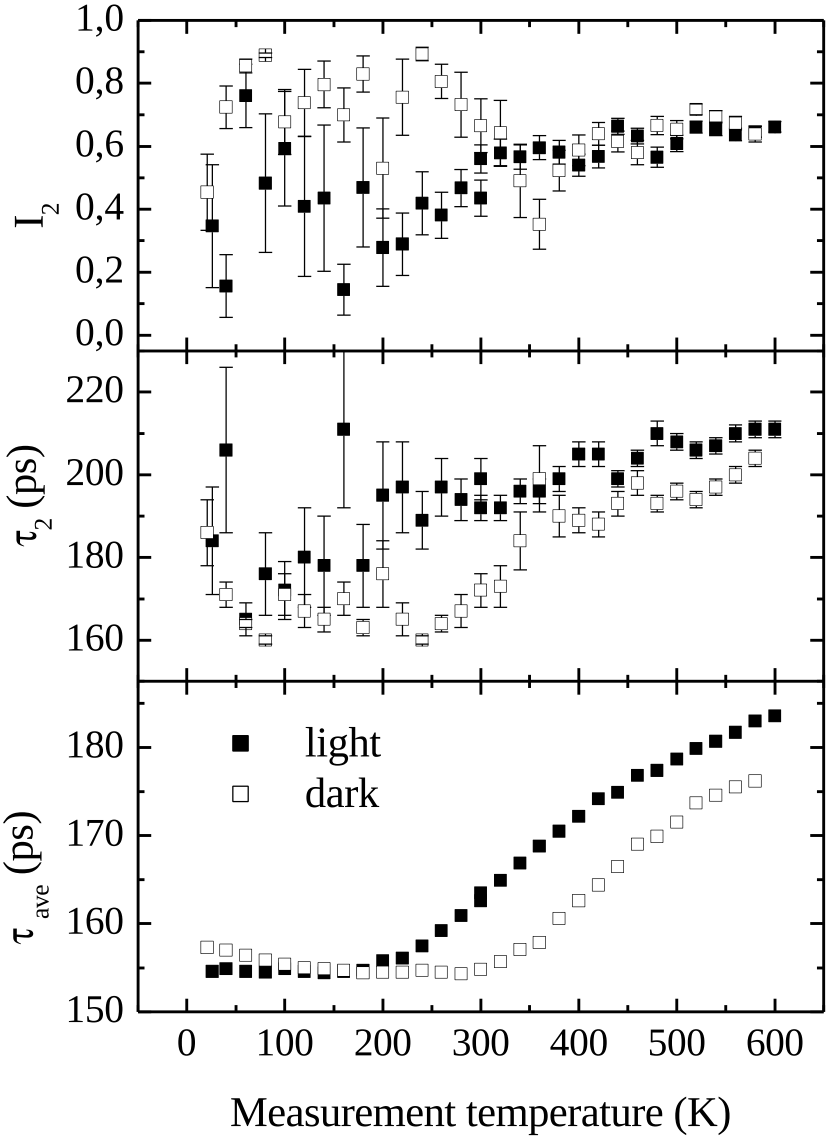
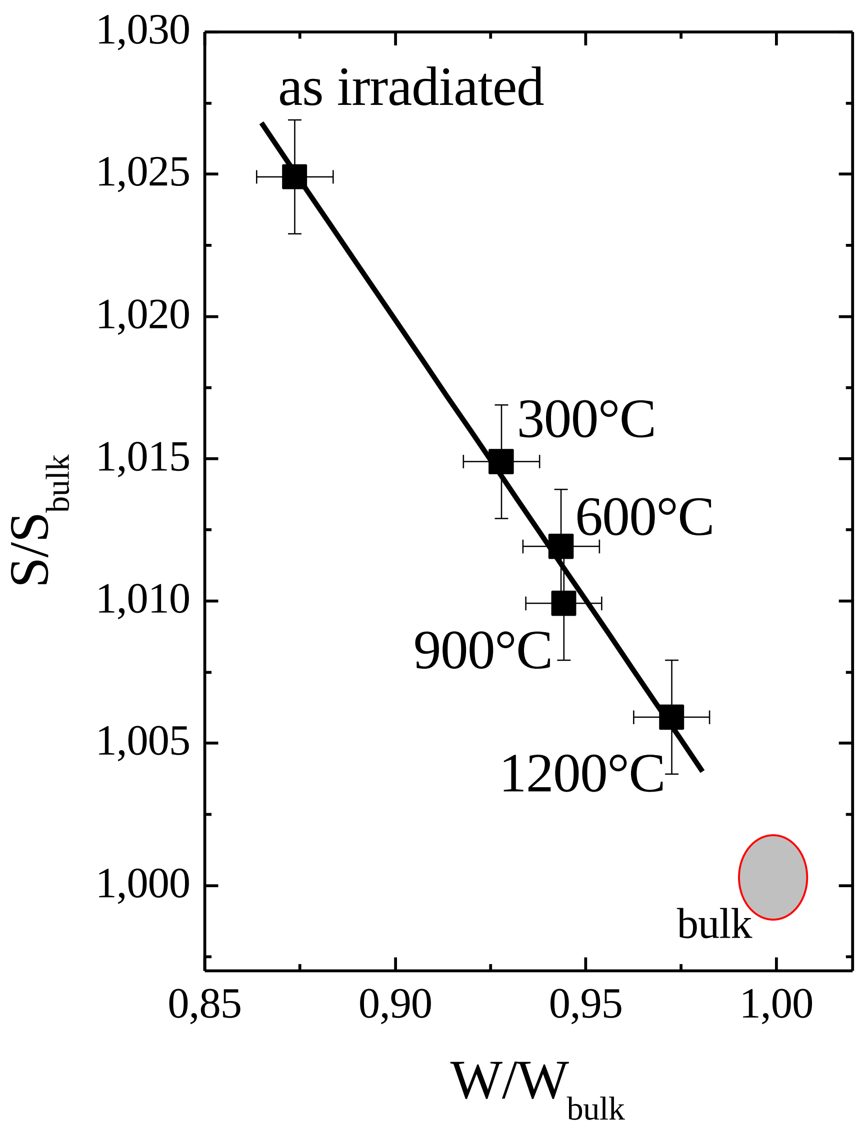

1,0
0,8
0,6
0,4
0,2
0,0
I_2
220
200
180
160
τ_2 (ps)
180
170
160
150
τ_{ave} (ps)
light
dark
0
100
200
300
400
500
600
Measurement temperature (K)

Figure 4



1,030
1,025
1,020
1,015
1,010
1,005
1,000
S/S_bulk
as irradiated
300°C
600°C
900°C
1200°C
bulk
0,85
0,90
0,95
1,00
W/W_bulk

Figure 5