Search of ultracold muonium generation material: muon spin rotation and relaxation study in SiC

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Abstract. Ultracold muonium (UCMu) is an important muonium (Mu) source for the generation of ultraslow muon beam for nanotechnological applications and understanding hydrogen dynamics in materials. In order to search for a new solid material for the generation of UCMu in vacuum, we have studied polycrystalline SiC using conventional muon spin rotation and relaxation method at low temperatures (5 K – 300 K). The high relaxation rates of Mu formed deep inside from the surface (full-stop case) and near the rear surface (half-stop case) were observed at low transverse field (TF 1.2 G). The relaxation rates of Mu at different temperatures in full-stop and half-stop cases were found to be the same within error-bars indicating the less possibility of emission of the UCMu from the surface of the SiC. We plan further study in KCl, porous silica, and chevron shaped electron rich microporuos materials.

1. Introduction

Muonium (Mu) is a bound state of positive muon (hereafter muon) and an electron. The ulatracold muonium (UCMu, Mu with low thermal energy) generation material can be used as source of muonium for nanotechnology and understanding hydrogen behavior in materials. A new Mu source material that can be operated near 20 K would reduce the energy spread of an ultraslow muon beam by 100 times compared to that of existing hot tungsten source [1, 2] operating near 2000 K. UCMu will aid in the achievement of a coherent and low-energy spread ultraslow muon beam for studies in nanoscience, materials surface science, three-dimensional material imaging [3, 4], the muon g-2 experiment, and in innovative instrumentation technology being developed in the Japan Proton Accelerator Research Complex (J-PARC), Japan, such as the transmission muon microscope and ultraslow muon microscope [4, 5, 6, 7].

Muon behaves as a light proton ($m_\mu \sim 1/9\ m_p$) with around three times larger magnetic moment ($\mu_\mu \sim 3.2\ \mu_p$) and acts as a sensitive probe to materials. Depending on the properties of the material and environment, the injected muon captures an electron and form Mu. Similar to the H-acceptor in n-type and donor in p-type materials [8, 9], muons can form different charge states (neutral Mu, Mu^+, Mu^-, diamagnetic muon, etc) in various samples [10, 11]. The Mu precessional frequency is around hundred times higher than that of muon at same magnetic field. Consequently, we can easily distinguish the Mu signal from that of the muon.

Several studies on the search of Mu production materials have been reported by different research groups. For example, study on tungsten [2], platinum, iridium [12], silica powder [13], silica aerogel [14], and SiO_2 films [16] are available in literature. Among them, two materials - hot tungsten [1] and laser ablated silica aerogel [15] are noticed as the Mu production material with relatively higher yield. Here, we are interested to search a material for the generation of UCMu to take advantage of the reduced energy spread when used as a source for muon based optics. We require a material having a large yield Mu at low temperatures (< 100 K). To search for new materials for generation of UCMu, we have started our study in the materials in which formation of Mu has already been reported without any information about the diffusion and emission of the Mu from the surface. First of all, we have studied n-type Si [17] in which we found the difference in relaxation rates of Mu stopped deep inside from the Si surface and near the surface indicating the emission of Mu from the surface. However, distance dependent (distance bewteen the Si surface and silver sheet set downstream) study suggested the origin of such difference in relaxation rates is ascribed to surface effect [18]. Our second material is SiC. Previously, Patterson et al [19] reported the formation and states of Mu in β-SiC and 6H-SiC at low temperature around 20 K. Lictchi et al [20] reported the hyperfine spectroscopy of neutral Mu impurity centers in 4H-SiC and 6H-SiC at field 6 T and temperature below 10 K. Bani-Salameh et al [21] reported the charge-state transitions of Mu in n-type, p-type and high-resistivity 6H-SiC in wide temperature range (5 - 1000 K). Celebi et al [22] presented the diamagnetic fraction and Mu behavior in 4H-SiC from low field study in temperature range (10 - 1400 K). Woerle et al [23] reported the fraction of diamagnetic muon and paramagnetic Mu in proton irradiated 4H-SiC using low energy muon beam available at PSI. Recently, Lord et al [24] reported the optically induced effects on muons implanted in 6H-SiC using a pulsed laser. Most of the studies were performed on the hexagonal structures of SiC. Here, we present the low field (TF 1.2 G) and low temperature (5 K - 300 K) study on polycrystalline SiC to test the formation and emission of Mu from the surface using conventional μSR method.

2. Experimental

The μSR experiments were performed in S1-area, S-line, Material and Life Science Facility (MLF), J-PARC using positive muon ($\sim$4 MeV). The polycrystalline silicon carbide (SiC) of dimension 10 mm $\times$ 10 mm $\times$ 0.3 mm was purchased from Ferrotec Material Technologies Corporation. Four pieces were tiled-up and the muon beam was injected into the sample through a thin Al foil (window of Ag thermal shield) as shown in Fig. 1. A silver (Ag) sheet (thickness 0.3 mm) was set downstream to SiC. The Ag sample holder is connected to helium cryostat placed in vacuum (10^{-5} Pa) connected to a flypast chamber. To achieve the two cases - stop all muons deep inside from the SiC surface (hereafter full-stop case) and half of the muon stop near the rear surface of SiC and half in Ag sheet (hereafter half-stop case), we tuned the muon beam momentum. Those two momentum were used for all half-stop and full-stop cases of other temperature dependent measurements. The beam collimetor size was ϕ15 mm. Transverse field (TF) measurements at 1.2 G and 20 G in the temperature range 5 – 300 K were performed.

3. Results and discussions

Figure 2 shows the superimposed time spectra of muon and Mu signals at TF 1.2 G at two selected temperatures (5 K and 100 K) in half-stop and full-stop cases in the SiC. The Mu formed in the SiC is quickly relaxed (within 1 μs) in both half-stop and full-stop cases. The spectra at 5 K and 100 K depicted that there is no significant temperature dependent effect on Mu relaxation. The spectra were analysed using a function composed of muon and Mu contributions (Eq. 1).

$$A(t) = A_\mu exp(-\lambda_\mu t)cos(\omega_\mu t + \phi_\mu) + A_{Mu}exp(-\lambda_{Mu}t)cos(\omega_{Mu}t + \phi_{Mu}) + B, \quad (1)$$

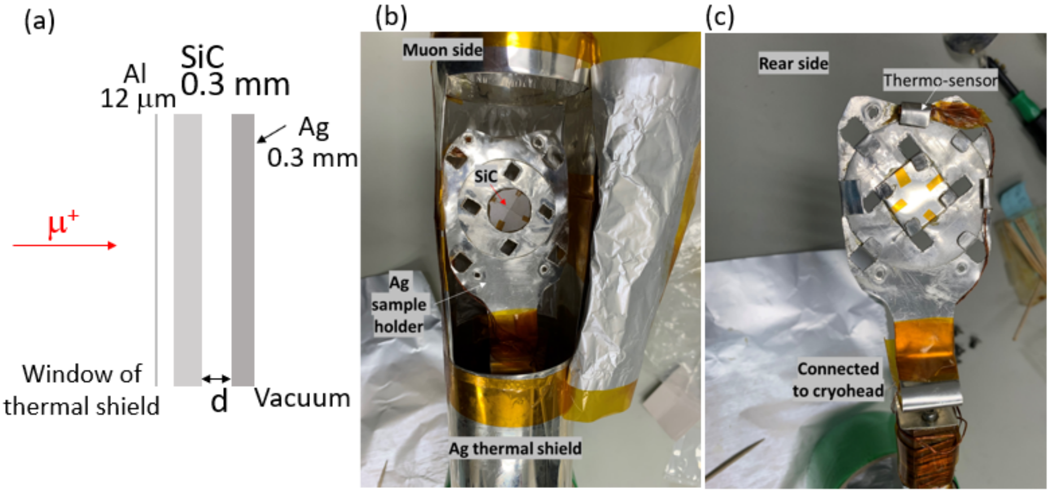

Figure 1. (a) Schematic diagram of the set-up. The distance d between SiC and Ag sheet kept 0 mm, (b) view from the muon side. The four square SiC pieces were tiled-up and hold by Ag holder inside the Ag thermal shield, (c) rear view image of the set-up. The thermal sensor position close to SiC is shown.

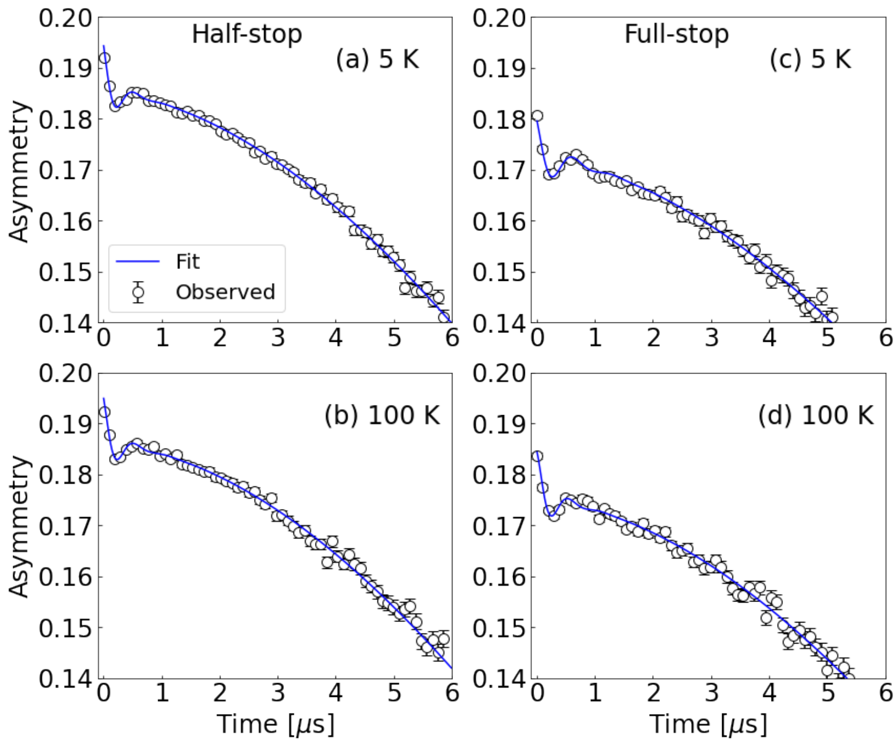

Figure 2. Superimposed time spectra of muon and muonium at TF 1.2 G. (a) half-stop at 5 K, (b) half-stop at 100 K, (c) full-stop at 5 K and (d) full-stop at 100 K.

where B is the time-independent background. The terms A_μ and A_{Mu} are the amplitudes of the spin precession corresponding to the polarization asymmetry for the μ^+ in diamagnetic states and Mu, respectively. The parameter λ_{Mu} is the muonium relaxation rate. The relaxation rate of μ^+ in diamagnetic species (λ_μ) is negligibly small with respect to λ_{Mu}. ω_μ and ω_{Mu} are the muon and Mu precession frequencies, respectively, and ϕ_μ and ϕ_{Mu} are the respective initial phases of their precessions. Under the transverse field of H(G), the spins of μ^+ and Mu take precession with the angular velocities of $\omega_\mu(\text{kHz}) = 2\pi\times13.553\times\text{H(G)}$ and $\omega_{Mu} = 2\pi\times1390\times\text{H(G)}$, respectively.

The temperature dependent relaxation rate of Mu (λ_{Mu}) in both full-stop and half-stop cases were presented in Fig. 3. The half-stop and full-stop values lie within error-bars at all temperatures. If the Mu would have emitted from the SiC surface then those will be stopped in the adjacent Ag sheet in which Mu converts into muon. In such situation, the difference in relaxation rate of Mu inside and in Ag is expected. It points out that there is less possibility of coming out of Mu from SiC surface. We will perform further study on porous silica, KCl, chevron shaped electron rich micro-porous materials, etc to continue the search of new material for generation of ultracold muonium.

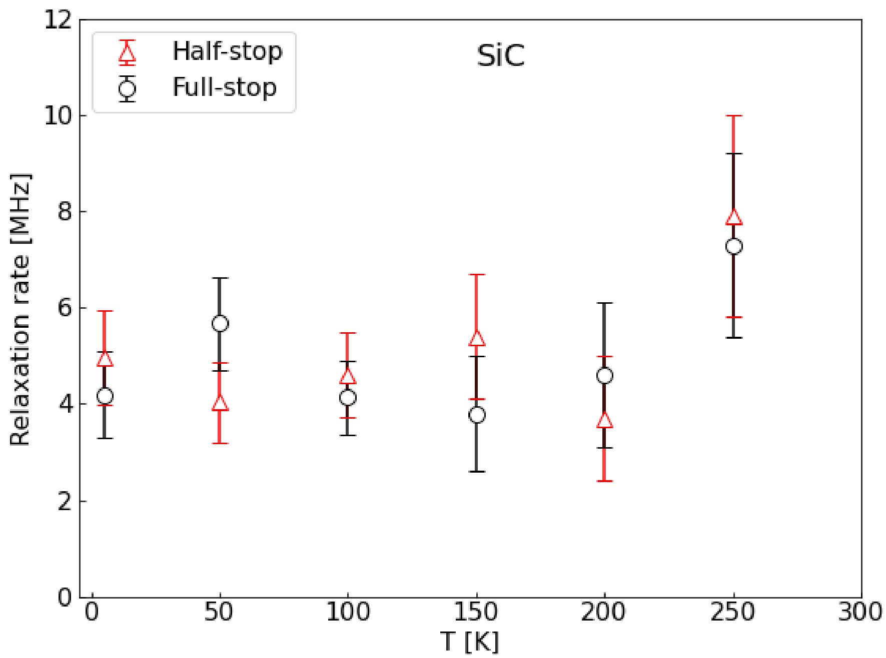

Figure 3. Relaxation rates of Mu at different temperatures in half-stop and full-stop cases in SiC.

4. Conclusion

We have performed conventional μSR measurement in polycrystalline SiC to study the ultracold Mu generation for Mu target materials. The temperature dependent relaxation rates of Mu stopped deep inside from the surface and near the rear surface of the sample shows the less possibility of emission of Mu from the SiC. We will continue our further study in porous silica, KCl, chevron shaped electron rich micro-porous materials, etc.

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