Muon Detection of Spin-Polarized Conduction Electrons Induced by Circularly-Polarized Direct Band Excitation in n-type Si

H.W.K. Tom,[*1] K. Nagamine,[*1,*2] K. Shimomura,[*2] K. Yokoyama,[*3] J. Muse,[*1]
K. Ishida,[*3] F.L. Pratt,[*4] I. Shiraki,[*5] A.D. Pant,[*5] and E. Torikai[*5]

We investigated the possibility that muon spin-relaxation can be used to detect the spin-polarization of conduction electrons in the indirect bandgap semiconductor Silicon. Spin-polarized conduction electrons can be detected optically in direct bandgap semiconductors (i.e., GaAs) through known selection rules at the bandgap. However, Silicon, arguably the most technologically important semiconductor, has no optical analog due to its indirect bandgap. μSR has intrinsic spin-polarization sensitivity and, if able to detect spin polarization in Silicon, may advance Si spintronics. Implanted muons in Si interact with electrons to form bound muonium states. In a mechanism originally proposed by Torikai[1)], anti-parallel conduction electrons may exchange with parallel bound electrons in triplet muonium converting it to singlet muonium which would be detectable by enhanced depolarization of the muon spin.

Earlier we demonstrated that μSR was sensitive to laser-injected spin-polarized electrons in n-GaAs[2)]. Circularly-polarized, 7 ns duration, laser pulses with photon energy tuned below bandgap injected 50% spin-polarized electrons throughout the bulk of a 350 micron thick wafer. Experiments at all B-field and wavelengths are consistent with the laser-excitation enhancing spin-relaxation of muons in only one species, Mu^-. The amplitude reduction is larger for anti-parallel polarized conduction electrons consistent with the proposed exchange mechanism.

We performed similar experiments on n-Si. Although it is generally accepted that optical spin-injection is forbidden by the indirect bandgap of Si, a recent density functional theory calculation by Nastos, et al.[4)] shows that at the direct bandgap, the degeneracy factors for the transitions are as shown in Fig. 1 (left)) and lead to a degree of spin polarization vs photon energy shown in Fig. 1 (right).

Samples were 300 μm thick wafers of n-Si with evaporated Au and ITO (Indium Tin Oxide) electrodes for voltage-biased transport of the injected electrons. Muons were implanted in the 100 μm region closest to the laser-excitation side of the sample. Typical data are as shown in Fig. 2 (Left), for the case of B=1000 G at 20K. The laser pulse arriving at 0.8 μs induces a step-like change in the F-B asymmetry that can reduce as much as 50% of the total F-B asymmetry in <300 ns. Unlike GaAs, however, the laser-induced change effects multiple species. Three species are known in n-Si: Tetrahedral (T) muonium, bond-centered (BC) muonium, and the negative ion (T) Mu^-.

*1 Physics and Astronomy, University of California, Riverside
*2 Muon Science Laboratory, IMSS, KEK
*3 RIKEN Nishina Center
*4 ISIS, Rutherford Appleton Laboratory
*5 Medicine and Engineering, University of Yamanashi

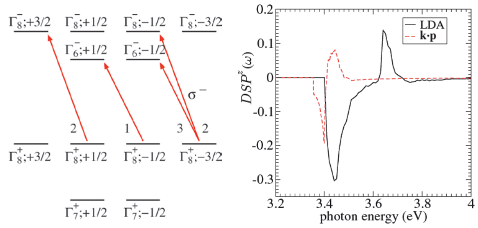

Fig. 1: Ref [4]. (L) Si interband transition degeneracies for σ^- excitation. (R) Degree of Spin Polarization vs photon energy in LDA and k·p approximations.

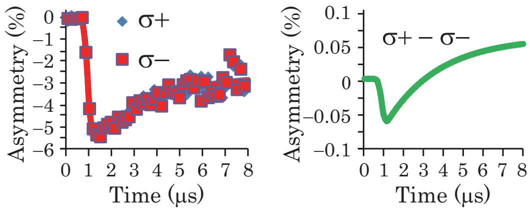

Fig. 2. (Left) n-Si F-B Asymmetry change induced by 372 nm laser excitation. σ^+ and σ^- changes and best fit. (Right) σ^+-σ^- best fit difference.

F-B Asymmetry vs time without laser excitation shows a fixed component and an exponentially decaying component, fitting A+Bexp(-γt). The laser-induced change (σ^+-Laser off) and (σ^--Laser off) can be fit by ΔA+ΔB exp(-γt). Here ΔA and ΔB are both ~ -2.5%. The solid blue and red lines are the best fits to the data for σ^+ and σ^-. The difference between the best fit lines (σ^+- σ^-) is shown in Fig. 2 (right). Spin-dependent ΔA_{+-}=0.073±0.082 and ΔB_{+-}=-0.14±0.13 with 25M events for each laser helicity (100M events total, 50M laser off). We will need significantly higher statistics (15X) to resolve this effect at <0.02% F-B asymmetry. We repeated this measurement at 12 photon energies spanning 3.32 to 3.64 eV, the spectral range in Fig. 1. The signs of ΔA_{+-} and ΔB_{+-} are opposite to each other within experimental uncertainty for all 12 photon energies although the sign of ΔA_{+-} was not always positive. The opposing signs are experimentally significant for the data set as a whole, but we have no explanation presently.

Future followup experiments will require finding ways to restrict the μSR signal to one species such as via ALC resonance, increasing signal to noise and statistics, and/or finding the optical wavelength of maximum spin-injection by some other technique (e.g. spin-polarized fluorescence).

References

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