Longitudinal Muon Spin Depolarization in Bulk $Si_{0.09}Ge_{0.91}$

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Introduction and Background

Silicon and Germanium are clearly important and widely used in the semiconductor industry. Over the course of the past two decades, there has been increased interest in expanding the scope of possibilities of devices by utilizing alloys composed of various amounts of both Silicon and Germanium. Applications with Silicon Germanium alloys ($Si_{1-x}Ge_x$) can utilize the traditional Si fabrication methods. Across the entire alloy range, $Si_{1-x}Ge_x$ maintains the same crystal structure and a mix of the electrical properties associated with Si and Ge. Our collaboration has been using Muonium (Mu) as an experimentally accessible analog to hydrogen in an ongoing project focused on investigating the H/Mu defect chemistry in Czochralski-grown $Si_{1-x}Ge_x$ alloys.

Our investigation has been focused on determining the donor and acceptor energies, obtaining hyperfine frequencies of paramagnetic Mu species and attempting to identify a variety of charge-state and site-change processes that may be present throughout the full range of alloy concentration.

This poster presents our preliminary findings on the recently examined bulk Czochralski-grown $Si_{0.09}Ge_{0.91}$.

The Experiment

- LF muon spin depolarazation measurements performed using the Helios spectrometer on M20 surface muon channel at TRIUMF in Vancouver, Canada
- ~15 million events per run & 10 μs time gate

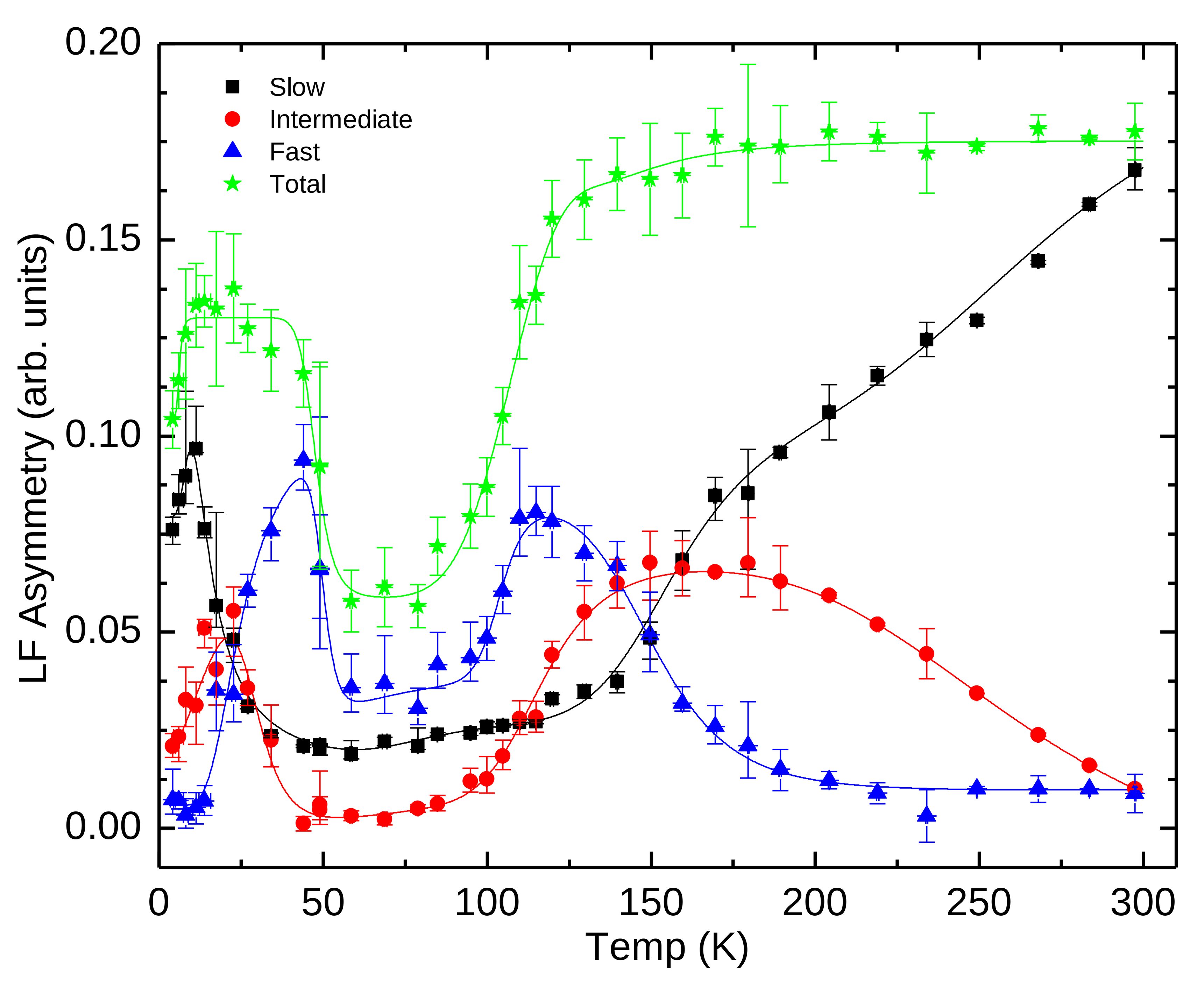

Fig. 1: Above is a plot of the asymmetry of each component of the signal as a function of temperature in an applied field of 70mT. The **slow**, intermediate and fast labels refer to the relaxation rates which range from **nominally non-relaxing**, 1 to 5 μs^{-1} and 10 to 30 μs^{-1}. From base temp up to around 225K, the **slow** signal separated very cleanly from the intermediate and fast however, separation of the intermediate and fast signals was not nearly as neat.

Observed Processes

Using LF-MuSR we have observed:

- Hole ionization & $Mu^0_T \rightarrow Mu^0_{BC}$ transition
  Both associated with shallow acceptor (base to ~50K)
- Observed two cyclic transitions involving: $Mu^0_T \leftrightarrow Mu^0_{BC}$
  Followed by hole ionization: $Mu^0_T \rightarrow Mu^-_T$
  Continues until hole capture drives final state to stable Mu^+_{BC} or terminated by BC ionization causing $Mu^0_{BC} \rightarrow Mu^+_{BC}$

Current & Future work

- Currently analyzing similar LF data $Si_{0.06}Ge_{0.94}$ & $Si_{0.19}Ge_{0.81}$
- Reported results on $Si_{0.09}Ge_{0.91}$ consistent with our findings on $Si_{0.06}Ge_{0.94}$ & $Si_{0.19}Ge_{0.81}$ showing clear shifts with differences in composition
- Overall goals include determining how cyclic processes evolve as a function of alloy content
- Additional data fitting & theoretical modeling are necessary to ensure accurate assignments for the processes preliminarily quoted here but also to extend to the rest of the Ge-rich compositions, as appropriate
- This and all previous SiGe work will be used to develop a comprehensive description of the Mu/H defect characteristics including the cyclic charge-state and site-change processes that occur and how these processes, features and characteristics vary as a function of alloy content.

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T < 60K (Slow)

Initially Mobile Mu^0_T
Interacts with neutral donors or ionized acceptors
Hole ionization to Mu^- (T > 10.5K)
E=3.5 ± 0.3 meV
RF results donor level [1,3]: E=4.5 ± 1 meV

T < 50K (Fast)

Initially Mobile Mu^0_T
To Shallow Mu Acceptor
To Mu^-
E=17.9 ± 1.7 meV

45–60K (Fast)

Mu^0_T to Mu^0_{BC} Transition
E=101.5 ± 2.3 meV
Est.[4,5]: E≈ 80 ± 30 meV

80–160K (Intermediate)

Mu^0_{BC} to Mu^0_T cycles
E=122 ± 21 meV

80–120K (Fast)

Mu^0_T to Mu^0_{BC} cycles
E=239.7 ± 1 meV

160–300K (Intermediate)

Mu^0_{BC} to Mu^0_T continuing cycle
Terminated by hole capture
$Mu^0_T + h^+$ to Mu^+_{BC}
Hole Ionization to Mu^-
Until hole capture dominates and can drive:
Mu^0_T to Mu^+_{BC} as long lived final state
E=153 ± 8 meV
Similar feature observed in TF [3]: E=155 ± 11 meV

T < 25K (Intermediate)

Initially Mobile Mu^0_T
To Shallow Mu Acceptor
E=2.1 ± 0.3 meV

25–50K (Intermediate)

Shallow Mu Acceptor
Switching into Mu^-_T detected by fast relaxing signal
Resulting in complete disappearance of the signal
E=17.5 ± 2.5 meV

50–60K (All)

Shallow acceptor disappears
Mu^0_T Remains mobile

60–130K (Slow)

Unidentified feature
E=41.7 ±2.1 meV

120–200K (Fast)

Mu^0_T to Mu^0_{BC} continuing cycle
Terminated by hole capture
$Mu^0_T + h^+$ to Mu^+_{BC}
Hole Ionization to Mu^-
Until hole capture dominates and can drive:
Mu^0_T to Mu^+_{BC} as long lived final state
E=161.5 ± 31.1 meV
Direct comparison to feature in slow signal:
130 –200 (slow): E=158 ± 3 meV

T > 180K (Slow)

Mu^0_{BC} to Mu^+_{BC} Final BC ionized state

Last two features:

130<T<200K: E=158 ± 3 meV
Corresponding rise to decay of fast signal

T > 200K: E= 200 ± 50 meV

Corresponding rise to the decay of the intermediate signal

References

[1] Carroll BR, et al., *Phys Rev B.* **82** (2010) 205205
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[3] Carroll BR, *Ph.D. dissertation*, Texas Tech University, 2010