The new β-NMR facility at TRIUMF and applications in semiconductors

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Abstract

A new facililty for conducting beta-detected nuclear magnetic resonance (β-NMR) investigations of condensed matter systems has recently been constucted at TRIUMF in Vancouver, Canada. The unique features of this new facility are described, and some preliminary results on $^{8}Li^{+}$ in GaAs are presented.

Key words: β-NMR, nuclear magnetic resonance, radioactive ion beams, nuclear probes

1 Introduction

Nuclear magnetic resonance (NMR) is an extremely powerful tool that finds applications in condensed matter physics and many other fields. In *conventional* NMR, approximately 10^{18} spins are needed to produce reasonable signals and hence it is mostly a bulk probe of matter. By contrast, related methods based on detection of radioactive atoms such as $\beta-$NMR, can improve this sensitivity quite dramatically. In one form of $\beta-$NMR, a beam of radioactive nuclei[1,2] is given a high

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degree of nuclear spin polarization and then implanted into the material being investigated. It turns out since the subsequent time evolution of the polarization is monitored through the anisotropic decay properties of the nuclei, about 10 orders of magnitude fewer spins are required than in conventional NMR. Consequently, $\beta-$NMR is ideally suited to studies of impurities in semiconductors and in particular those without an unpaired electron (i.e. diamagnetic centers). Furthermore, the technique has such high intrinsic sensitivity that it can also be applied to semiconductor nanostructures where conventional methods for investigating point defects lack the required sensitivity.

Recently, a unique facility for conducting $\beta-$NMR experiments has been constructed at TRIUMF (TriUniversity Meson Facility) in Vancouver, Canada. Intense beams of low energy, highly spin-polarized, radioactive ^{8}Li are currently available for carrying out these $\beta-$NMR studies. This paper will describe the facility, show some preliminary results on a prototypical semiconductor GaAs, and discuss future prospects.

2 The $\beta-$NMR facility at TRIUMF

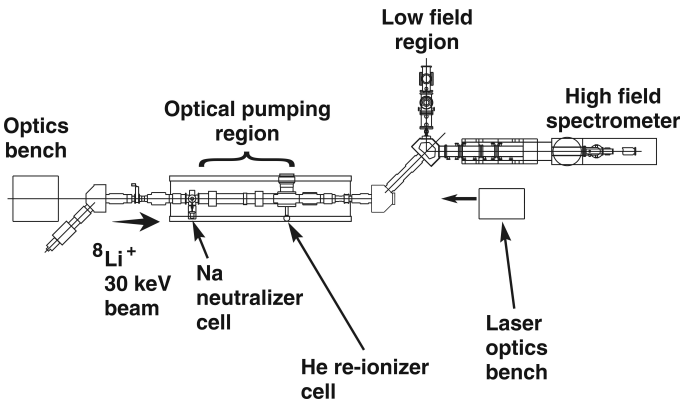

Fig. 1. Top view of the layout of the $\beta-$NMR facility at TRIUMF.

The ISAC (Isotope Seperator and Accelerator) radioactive beams facility at TRIUMF has the capability of delivering a continuous beam of $\approx$ 30 KeV ^{8}Li$^+$ with a typical flux of $\approx 10^7$/s. [The ^{8}Li nucleus has a spin of 2, a lifetime of $\tau = 1.21$s, a gyromagnetic ratio $^8\gamma = 630.15$Hz/G, and an electric quadrupole moment $Q = +33$mB.] This beam of ions, initially unpolarized, is introduced into the $\beta-$NMR beam-line shown in Fig. 1.

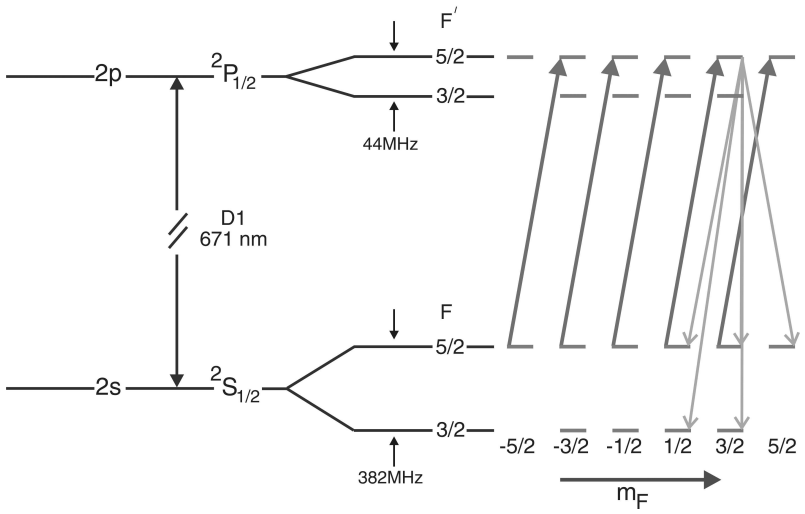

Fig. 2. Optical pumping scheme for polarized ^{8}Li. For clarity, the optical transitions from the $^2S_{1/2}, F = 3/2$ to the $^2P_{1/2}, F = 5/2$ are not shown.

The polarization of the $^8Li^+$ nuclear spin is achieved *in-flight* by a collinear optical pumping method [3]. The first step is to neutralize the ion beam by passing it through a Na vapor cell. The atomic $^8Li^0$ beam, still at 30 KeV, then drifts 2 m in the optical pumping region in the presence of a small longitudinal magnetic holding field of 1 mT. In this region, energy levels related to the Doppler-shifted D1 transition of $^8Li^0$ ($2s^2S_{1/2} \rightarrow 2p^2P_{1/2}$), occuring at $\approx$ 671 nm, are pumped with a beam of circularly polarized light. The polarization scheme of $^8Li^0$ is shown in Fig. 2. The ground and first excited atomic levels are split by the hyperfine coupling between total spin states $F = 5/2$ and $F = 3/2$. For circularly polarized light with positive helicity, $\Delta M_F = +1$ during excitation whereas the atom decays spontaneously with $\Delta M_F = 0, +1, -1$. In our system, the levels corresponding to $^2S_{1/2}, F = 3/2$ and $^2S_{1/2}, F = 5/2$ are optically pumped into the $^2P_{1/2}, F = 5/2$ states. There is time for about 10-20 cycles of absorption and spontaneous emission which lead to a highly polarized atom spin state ($F = 5/2, M_F = 5/2$) and therefore a well-defined state of nuclear spin $M_I = 2$. At the end of the drift region, the atomic beam is re-ionized by passing it through a He vapor cell, which strips one electron from Li^0. With this system, we have managed to attain polarizations as high as $\approx 70\%$.

The polarized ion beam is then passed through two 45 degree electrostatic bending elements which divert the beam into one of three experimental stations. Since the beam optics are all electrostatic the polarization direction is unchanged by these bends. Two of the stations, labelled "low field spectrometer" and "high field spectrometer" in Fig. 1, are used for condensed matter research. The Li enters the low field station with polarization transverse to the beam momentum while it enters the high field station with polarization longitudinal to the beam momentum.

In both spectrometers, a non-resonant "transmission line" Helmholtz coil is used

to introduce either a CW or a pulsed radiofrequency (RF) magnetic field H_1 that is perperdicular to the static field H_0. The field H_0 is applied parallel to the initial Li spin direction and has maximum value of ≈ 9 T in the high field spectrometer (provided by a superconducting solenoid) while in the low field spectrometer, the maximum H_0 is ≈ 20 mT (provided by Helmholtz coils). The beam spot at the sample is about 3 mm in diameter. As in standard magnetic resonance, when the RF field approaches the resonance condition, the polarization of the ^{8}Li is "destroyed" as it precesses in the oscillating field. The decay β electron ($^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + \nu_\mathrm{e} + \mathrm{e}^-$) is emitted preferentially in the direction of the Li spin at the time of its decay. Hence, the evolution of the Li polarization can be monitored by placing fast plastic scintillation detectors forward and backward to the initial Li spin direction to detect the βs. Currently, an ultrahigh vacuum (UHV) compatible cryostat exists at the high-field station and another one is being installed on the low-field station. [Spin-lattice relaxation of the implanted $^8\mathrm{Li}^+$ can also be measured. Here, the $^8\mathrm{Li}^+$ beam is pulsed and the time dependence of the polarization is measured (in the absence of the RF field) after the beam pulse has ended.]

One important feature of both spectrometers is that the ions can be implanted over a wide range of energies (1-90 KeV), corresponding to an average implantation depth between 6 nm and 400 nm respectively. This can be accomplished by placing each spectrometer on a high voltage platform which is electrically isolated from ground. The energy of the implantation, and hence the average depth into the sample is controlled by adjusting the platform bias voltage. The UHV cryostat on the high-field station already resides on such a platform while another will be constructed for the low-field spectrometer. Hence, the $\beta-$NMR facility at TRIUMF has the capability to investigate materials with nanometer thicknesses.

3 Preliminary Results in GaAs

Making use of the new TRIUMF $\beta-$NMR facility, we have recently initiated an experimental program for studying the kinetics and spectroscopy of Li in semiconductors. Some initial results are discussed in this section. The experiments were conducted in the high-field spectrometer described above. The $^8\mathrm{Li}^+$ is implanted into a semi-insulating GaAs sample ≈ 350 μm thick and the static magnetic field H_0 of approximately 3 T is applied parallel to a $\langle 100 \rangle$ direction.

The inset in Fig. 3 shows the $\beta-$NMR resonances near room temperature and at low temperature. At all temperatures studied, there is a signal of large amplitude at the ^{8}Li Larmor frequency, indicating that Li is located at highly symmetric sites and hence experience no resolved quadrupole splitting. The possible sites are the two interstitial tetrahedral or two substitutional sites, but from our current data we cannot spectroscopically distinguish between these possibilities or whether multiple sites are occupied, as inferred from emission channeling measurements of Li in GaAs [4].

There is a strong temperature dependence of the linewidth, as is shown in the main part of Fig. 3. The linewidth is attributed to nuclear dipolar interactions

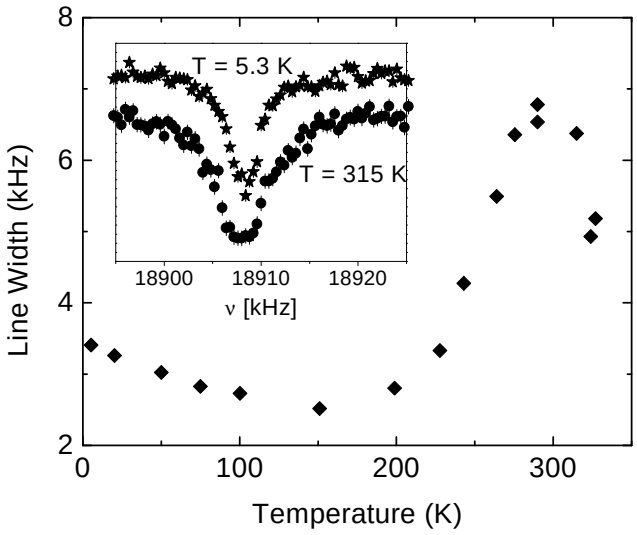

Fig. 3. The inset shows the resonances in GaAs at two temperatures. The main part shows the temperature dependence of the linewidth.

between the static Li and other magnetic moments in the sample. The host ^{69}Ga, ^{71}Ga and ^{75}As nuclei (all of which have spin 3/2) are certain to contribute to the linewidth, as will intrinsic defects such as vacancies that are created during the implantation process. (There is also some additional broadening due to the RF power, but it is kept constant at all temperatures.) There appears to be a slight decrease in the linewidth from 5 K to 150 K, followed by a significant broadening above 150 K. The linewidth peaks at about 290 K before decreasing once again. [The amplitude of the resonance signal indicates that at low temperatures, about 70% of the Li end up in a high symmetry site, while by 220 K, all of the Li are in such sites.] These data indicate that the "environment" around the Li is changing significantly above 150 K. A possible scenario for this change is that above 150 K, the Li approaches implantation-created vacancies that are in its vicinity, and the broadening of the resonance signal is due to small unresolved quadrupolar splittings. At higher temperatures, Li might be "occupying" the vacancy (e.g. substitutional Li_{Ga}) where the quadrupolar splitting is identically zero, and hence the linewidth is observed to decrease. Whether such a picture is consistent with measurements of the intrinsic diffusivity of Li in GaAs[5] requires further analysis, as well as additional site sensitive measurements. (In addition, we cannot rule out that the vacancy is moving, as suggested by Lindner *et al.* [6].)

4 Conclusions and Future Prospects

In this paper, we have described the newly constructed $\beta-$NMR facility at TRIUMF and discussed some initial measurements of ^{8}Li in bulk GaAs using this facility. Measurements that can provide site sensitive information such as level crossing cross-

relaxation, double resonance, etc. are planned for the near future in order to enhance our understanding of the behavior of Li in this semiconductor. It should be noted that while intense beams of ^{8}Li are currently available for use at TRIUMF, polarization schemes for probes such as ^{12}B, ^{11}Be, ^{15}O and ^{19}O, are also being planned. The eventual existence of such a diverse range of interesting probes, coupled with the potential of stopping them in nanometer scale semiconductors, will hopefully make the TRIUMF facility a premier location for conducting $\beta-$NMR studies of defect physics in semiconductors. Interested researchers are invited to participate.

Acknowledgements

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Figures:

Fig.1: Top view of the layout of the $\beta-$NMR facility at TRIUMF.

Fig.2: Optical pumping scheme for polarized ^{8}Li. For clarity, the optical transitions from the $^2S_{1/2}, F = 3/2$ to the $^2P_{1/2}, F = 5/2$ are not shown.

Fig.3: The inset shows the resonances in GaAs at two temperatures. The main part shows the temperature dependence of the linewidth.