Beta-NMR study of $^{58}$Cu in Si


Cu impurities in Si devices are considered serious contaminants. The short-lived $\beta$ emitter $^{58}$Cu ($I^+=1^+$, $T_{1/2}=3.2\text{ s}$) is attractive for studying the behavior of Cu impurities in Si using the $\beta$-NMR technique, which will provide unique information about the mechanism of fast Cu diffusion$^1$ or the property of Cu-dopant complex that is related to the gettering technique.$^2$ The $N=Z$ odd-odd nucleus $^{58}$Cu, consisting of $^{56}$Ni plus one proton and one neutron, is also interesting in terms of the nuclear moment, from which we can study the proton-neutron interaction in $pf$-shell nuclei.$^3$

We detected an NMR signal of $^{58}$Cu in Si in 2010, and the magnetic dipole moment $|\mu|^{^{58}\text{Cu}} (0.46 \pm 0.03)\text{nT}$ was obtained.$^4$ In 2011, Vingerhoets et al. greatly improved the measurement accuracy using collinear laser spectroscopy, achieving $\mu^{^{58}\text{Cu}} = +0.570 \pm 0.002)\mu_\text{N},$ which is about $20\%$ larger than ours. One possibility for the discrepancy is the existence of an electric field gradient (EFG) which could be generated if some defects are formed at a $^{58}$Cu site in Si, though a cubic symmetry site without EFG is expected in terms of the crystal structure of Si. If the EFG exists, the NMR spectrum should split into two lines with frequencies of $\nu_\pm = \nu_0 \pm \nu_Q/2$ in the case of $J=1$, where $\nu_0$ and $\nu_Q$ are the carrier frequency and the quadrupole splitting frequency, respectively. In this case, our previous NMR line may have originated from $\nu_-$. In the present study, we have applied the multi-radiofrequency (RF) ($\beta$-NQR) technique$^5$ to the $\beta$-NMR measurement of $^{58}$Cu in Si to search for a quadrupole splitting in order to verify the above picture and to solve the discrepancy problem.

The experimental method is similar to our previous one.$^4$ Spin-polarized $^{58}$Cu nuclei were produced through the charge exchange reaction of $^{58}$Ni by impinging a $^{58}$Ni primary beam at 63 MeV/u, provided by the RIKEN ring cyclotron with a typical intensity of 100 particle nA, on a 0.5-mm thick Be target. Fully stripped $^{58}$Cu$^{29+}$ ions were separated by the RIKEN projectile fragment separator (RIPS) and were implanted into a single crystal sample of B-doped Si at 15 K with the crystal (001) orientation set parallel to the external magnetic field $B_0 = 0.93\text{ T}$, the same condition as in the previous experiment. A pair of resonance frequencies $\nu_\pm$ was searched for by changing both $\nu_0$ and $\nu_Q$, using the $\beta$-NQR technique in which two frequencies were applied in series as $\nu_+ \rightarrow \nu_+ \rightarrow \nu_-$ during the RF duration to inverse spin polarization of $^{58}$Cu.

The resonance was found at $\nu_0 \sim 4.1\text{ MHz}$ and $\nu_Q \sim 2.6\text{ MHz}$. The $\nu_Q$ spectrum at $\nu_0 = 4.00 - 4.15\text{ MHz}$ is shown in Fig. 1, from which $\nu_Q = 4eQ/3h(3\cos^2\theta-1) = (2.6 \pm 0.4)\text{ MHz}$ was obtained. The EFG $q$ will be obtained using the known $Q$ moment of $^{58}$Cu$^5$ after determining the angle $\theta$ between the main axis of the EFG and $B_0$ from the crystal orientation dependence of $\nu_Q$. $|\mu|^{^{58}\text{Cu}} = (0.58 \pm 0.01)\mu_\text{N}$ was obtained from $\nu_0$, which is in agreement with the data reported by Vingerhoets et al.$^5$ The difference between the present $\mu^{^{58}\text{Cu}}$ and the previous one$^4$ is mostly explained by the quadrupole splitting.

![Fig. 1. Beta-NQR spectrum of $^{58}$Cu in Si.](image_url)

References