MAR10-2009-001422

Abstract for an Invited Paper
for the MAR10 Meeting of
the American Physical Society

Magnetic spin resonance of hydrogenic phosphorus donors in silicon

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A variety of electron paramagnetic resonance (EPR) measurements of an ensemble of phosphorus donors in silicon has lead to following intriguing discoveries. Electrically detected magnetic resonance (EDMR) at low magnetic fields (<200G) has revealed transitions involving superposition states between phosphorus electron and nuclear spins. Such states emerge because the hyperfine term overwhelm the electron Zeeman term at such low magnetic fields. A continuous control of the degree of the superposition by applied magnetic field has been demonstrated. Extremely long coherence times ∼0.6 s at 2K of electron spins bound to phosphorus and ∼3 s at 6K of ^{31}P nuclear spins have been obtained by pulse-EPR and ENDOR of an isotopically enriched ^{28}Si single crystal (99.992%). Making the Si crystal nearly monoisotopic led to elimination of docoherence due to ^{29}Si nuclear spins. Not only the electron spin but also phosphorus nuclear spin decoherence time was found to depend strongly on the phosphorus concentration in the range 8x10^{13}-4x10^{15} cm^{-3}. Unexpected observation of shifts in ^{31}P nuclear transition energies (ENDOR peak positions) with the change in the background silicon isotopic composition is also reported. The four nearest neighbor silicon isotopes of phosphorus are shown to affect strongly the nuclear transition energy of ^{31}P. Experimental results will be discussed in the context of isotope effect arising from differences in the nuclear mass and spins. This work has been performed in collaborations with S. Tojo, H. Morishita, M. Eto, L. S. Vlasenko, and groups lead by K. Semba, M. L. W. Thewalt, S. A. Lyon, J. J. L. Morton, and M. S. Brandt. Financial supports by Grant-in-Aid for Scientific Research #18001002, NONOQUINE, JST-DFG Strategic Cooperative Program, and Global Center of Excellence at Keio University are greatly appreciated.