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## Efficient dynamic nuclear polarization of phosphorus in silicon in strong magnetic fields and at low temperatures

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### Abstract

© 2014 American Physical Society. Efficient manipulation of nuclear spins is important for utilizing them as qubits for quantum computing. In this work we report record high polarizations of  $^{31}\text{P}$  and  $^{29}\text{Si}$  nuclear spins in P-doped silicon in a strong magnetic field (4.6 T) and at temperatures below 1 K. We reached  $^{31}\text{P}$  nuclear polarization values exceeding 98% after 20 min of pumping the high-field electron spin resonance (ESR) line with a very small microwave power of 0.4  $\mu\text{W}$ . We evaluate that the ratio of the hyperfine-state populations increases by three orders of magnitude after 2 hours of pumping, and an extremely pure nuclear spin state can be created, with less than 0.01 ppb impurities. A negative dynamic nuclear polarization has been observed by pumping the low-field ESR line of  $^{31}\text{P}$  followed by the flip-flip cross relaxation, the transition which is fully forbidden for isolated donors. We estimate that while pumping the ESR transitions of  $^{31}\text{P}$  also the nuclei of  $^{29}\text{Si}$  get polarized, and polarization exceeding 60% has been obtained. We performed measurements of relaxation rates of flip-flop and flip-flip transitions which turned out to be nearly temperature independent. Temperature dependence of the  $^{31}\text{P}$  nuclear relaxation was studied down to 0.75 K, below which the relaxation time became too long to be measured. We found that the polarization evolution under pumping and during relaxation deviates substantially from a simple exponential function of time. We suggest that the nonexponential polarization dynamics of  $^{31}\text{P}$  donors is mediated by the orientation of  $^{29}\text{Si}$  nuclei, which affect the transition probabilities of the forbidden cross-relaxation processes.

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