DYNAMIC NUCLEAR POLARISATION IN P-DOPED SILICON BY MICROWAVE ULTRASONICS

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Abstract. We have investigated the dynamic nuclear polarisation (DNP) of ^{29}Si nuclei in highly doped silicon single crystals. The saturation of the electronic Zeeman levels in a magnetic field of 3.3 kG at 1.6°K was obtained using microwave ultrasonics of about 9 GHz. The ultrasonic waves were generated in a cavity by means of a transducer consisting of a thin film of CdS evaporated on the polished surface of the silicon. Preliminary results obtained with a silicon-rod of 2 × 2 × 12 mm cut with the long axis parallel to the ⟨110⟩ direction rendered a reduction of the NMR signal to about $\frac{1}{3}$ in agreement with the expected negative sign of the DNP

There are two mechanisms for dynamic nuclear polarisation (DNP), namely, 1) DNP caused by relaxation processes (Overhauser effect); 2) DNP originating from the simultaneous flip of two spins when absorbing a quantum from the r.f.-field (solid state effect).

Moreover, DNP by relaxation can also occur in solids provided there is a suitable time dependence of the interaction between the two spins. Earlier examples of such an Overhauser effect in solids were the DNP of ^{7}Li in Li metal [1] and of ^{29}Si in highly P-doped silicon [2]; in both cases the DNP results from the interaction of the nuclei with the conduction electrons.

The DNP which can be obtained is given by

$$\langle I_z \rangle = I_0 (1 + \xi f s \gamma_S / \gamma_I) , \tag{1}$$

where ξ is a coupling parameter; in the case of the scalar coupling of the conduction electrons with the ^{29}Si nuclei in our case $\xi = -1$. The leakage factor $0 < f < 1$ can be set $f = 1$ as a very good approximation in our case. The saturation parameter $0 < s < 1$ measures the necessary deviation of the population of the electronic Zeeman levels from the Boltzman equilibrium. This deviation is usually obtained by saturating the ESR transitions between these levels which requires in a magnetic field of several kG a frequency in the microwave region. In all measurements with highly doped silicon made so far, and even more so in metals, very small particles with a diameter $d < 1\mu$ had to be used because of the skin effect.

The aim of our experiment is to investigate single crystals with dimensions of the order of several mm and to saturate the electronic Zeeman levels by microwave ultrasonics in order to avoid the skin effect. The possibility of generating microwave ultrasonics has received increasing attention in the last decade after the pioneering work of Bömmel and Dransfeld [3], and Jacobsen [4].

While several mechanisms such as the Raman process contribute to the electronic relaxation at 4.2°K and above, the dominating spin-lattice relaxation mechanism at very low temperatures is the direct process [5]. Since in the narrow range of about 5 MHz corresponding to the electronic line width the number of thermal phonons is very small, one may assume without going into the details of the interaction with the electronic spins that it should be possible to produce more phonons of this frequency by ultrasonics and to saturate the ESR transitions.

We decided to work in a magnetic field of about 3.3 kG at a microwave frequency of about 9 GHz at 1.6°K. The skin depth of the corresponding

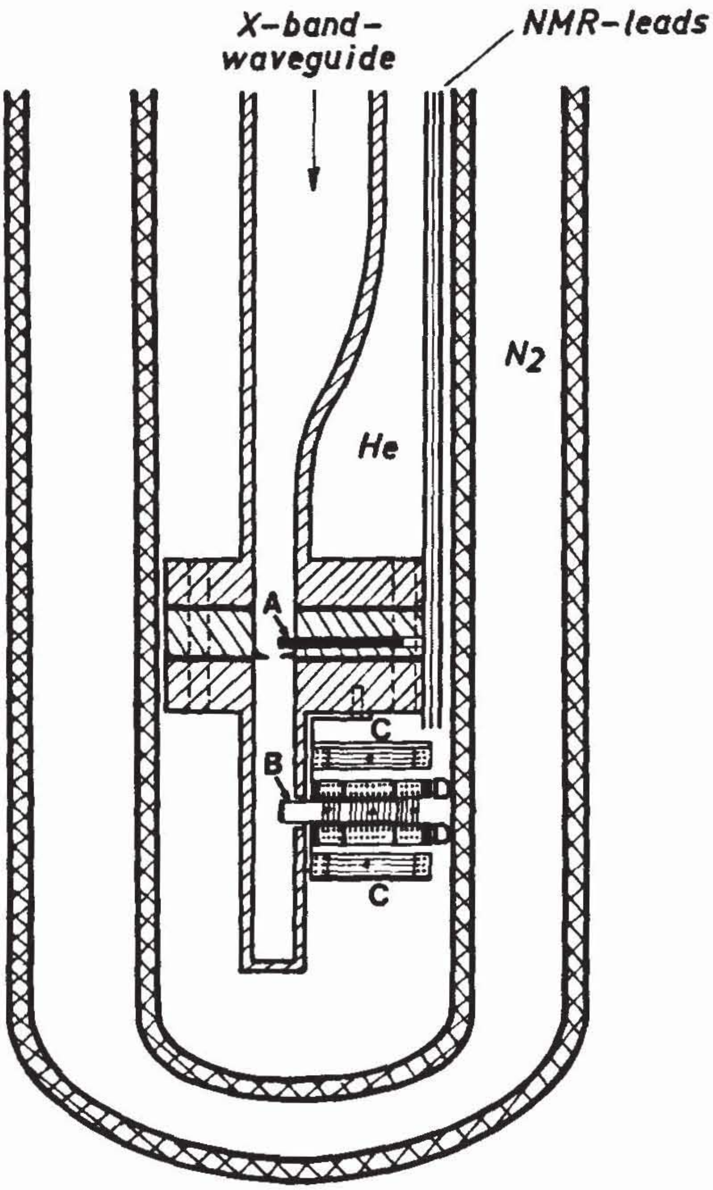

Fig. 1. Apparatus for the detection of DNP generated by microwave ultrasonics. A = Iris, B = sample, C = Transmitter coils, D = receiver coils.

^{29}Si NMR frequency of 2.8 MHz is estimated to be of the order of 2 mm. The apparatus is shown schematically in the first slide. The X-band frequency is guided through the helium dewar and coupled with an iris into a rectangular cavity excited in the TE 101 mode, the shorter side of which is reduced to 4 mm in order to increase the electric field. The microwave ultrasonics are generated by a CdS transducer [6] of a thickness of the order of 2μ evaporated on the polished surface of a silicon rod of the dimensions of $2 \times 2 \times 12$ mm. The silicon rod extends only a fraction of 1 mm into the cavity; its main part is outside the cavity surrounded by the NMR coil. The NMR signal was detected with a modified Bloch-head. The spin-lattice relaxation of the ^{29}Si nuclei was of the order of 20 min at 2×10^{19} phosphorus atoms per cm^3.

The coupling is known to be dominantly scalar, $\xi = -1$, and the magnetogyric ratio γ_I of the ^{29}Si is negative as well as γ_S of the electron. Consequently, we would expect a negative DNP, i.e. first a decrease of the signal, a reversal and if the effect becomes larger, an amplified emission signal. Preliminary measurements using a sample containing 2×10^{19} phosphorus atoms per cm^3 cut with the long axis parallel to the $\langle 110 \rangle$ direction have shown a reduction of the signal to about $\frac{1}{3}$ when irradiating with the resonance frequency.

Experiments with different P-atom concentrations and different directions of the long axis are being made. Our main experimental difficulty arises from the CdS transducer; so far we are unable to prepare the thin CdS layers with reproducible properties.

One reason for the small effect is unsufficient saturation; the incident power into the cavity was about 100 mW of which at least 30 dB are lost in the transducer. The most important question when observing such a small effect is, of course, if the electron saturation is really caused by ultrasonic processes or if it could be induced in the surface of the sample by electromagnetic radiation leaking out from the cavity. However, we feel certain that this is not the case since no effect at all was observed without the CdS transducer.

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