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Sensitivity analysis of magnetic field sensors utilizing spin-dependent recombination in silicon diodes

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ABSTRACT

An analysis of the magnetic field sensitivity that could be achieved in a sensor utilizing spin-dependent recombination (SDR) in silicon diodes is presented. Based on current theories of spin-dependent recombination and shot noise in diodes it is predicted that conventional silicon diodes may be used as detectors in a resonant magnetic field sensors with better than 3 μT resolution in a 1 Hz bandwidth – adequate for applications such as compassing, current sensing, position sensors and non-contact switches. A semiconductor device optimized for maximum SDR response will theoretically achieve a resolution on the order of 1 nT.

1. Introduction

Spin-dependent recombination (SDR) is an effect in which the recombination rate of electrons and holes in semiconductors depends on the spin polarization of the carriers. This spin polarization can be changed by exciting the system with ac electromagnetic fields at the electron spin resonance (ESR) frequency, corresponding to the energy difference between spin up and spin down states in a dc magnetic field, B_{dc}. Detecting ESR through the resulting changes in the recombination rate is known in the literature as electrically detected magnetic resonance (EDMR).

The schematic in Fig. 1 illustrates the frequency–field relationship for electron spin resonance: the resonance frequency, f_{ESR}, is proportional to the energy difference, ΔE, between the spin up and spin down states. ΔE in turn is proportional to the magnitude of the dc magnetic field, B_{dc}. As a result, the ESR frequency is directly proportional to the dc magnetic field. I.e., $f_{ESR} = \gamma B_{dc}$ where γ is the gyromagnetic ratio of the electrons. Of key importance is that γ is temperature-insensitive, allowing for the possibility of realizing an accurate, calibration-free magnetometer or magnetic field sensing technology in silicon. Surprisingly, although EDMR has been widely used to characterize defects in silicon crystals and devices, it has never been exploited directly for any technological application.

The change in recombination rate that results from the reorientation of spins at ESR is manifest in changes in the current–voltage characteristics of semiconductor devices such as diodes and transistors. Thus, it becomes possible to devise an electronic circuit that measures the magnitude of the dc field by determining the frequency at which a maximum change in device characteristics is detected. Such a resonant magnetometer could then be readily implemented as a standard-cell design in commercial silicon integrated circuit technology, requiring no specialty processing or materials.

2. Spin-dependent recombination

EDMR was discovered in 1966 by two independent groups, Maxwell and Honig [1] and Schmidt and Solomon [2]. They observed a reduction in the photoconductivity of Si samples, cooled to liquid He temperatures, when these where subjected simultaneously to dc and resonant ac magnetic fields. A similar effect was reported at room temperature in 1972 by Lépine [3], who attributed the effect to an increase in carrier recombination rate when ESR conditions were met.

Since its discovery, EDMR based on SDR has become a well-established method to characterize defects in semiconductor materials and devices [4–13]. So far, EDMR has not found any direct technological application. However, several features of EDMR make it of particular interest for potential use in integrated magnetic field sensors:

1. It occurs in Si, the most common commercial semiconductor.
2. It affects the I–V characteristics of common devices used in CMOS technology.
3. It can be detected with good sensitivity even in sub-micron scale devices.

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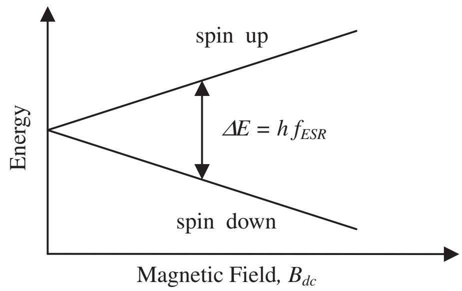

Fig. 1. Energy level for an electron in a magnetic field. The energy difference between spin up and spin down is proportional to the magnetic field.

4. The magnitude of the EDMR signal is independent of field strength, making it useful for low-field sensing.

Early theories supposed that the SDR effect was due to spin polarization of the conduction electrons and paramagnetic recombination centers by the dc field. However, these theories predict changes in recombination rates several orders of magnitude smaller than what is observed experimentally and do not account for the observed invariance with field strength. A physical model that is consistent with most experimental results was proposed by Kaplan, Solomon and Mott (KSM) [14–16]. The KSM theory assumes a Shockley–Read–Hall recombination process [17–19] in which electrons and holes are first captured at a recombination center, forming relatively long-lived pairs, before recombining. These pairs can either annihilate each other through recombination or dissociate back into free electrons and holes. Conservation of angular momentum dictates that only pairs with opposite spin (singlet pairs, denoted by '*s*' in Fig. 2) can recombine. Pairs captured in the singlet state recombine quickly while pairs with the same spin (triplet pairs) cannot recombine. This leads to an accumulation of stable triplet pairs, which, by occupying the recombination centers, block further recombination. The recombination rate can be enhanced by converting the triplet pairs into singlet pairs via electron spin resonance. This process is illustrated in Fig. 2.

The KSM model can be evaluated numerically by considering the transition rates for capture, dissociation and recombination. Assuming that the recombination rate for triplet pairs is negligible, it is found that the steady-state recombination rate without ESR excitation is given by [14,20]

$$R = W_C\left[1 - 2\lambda \ln\left(\frac{1+2\lambda}{2\lambda}\right)\right], \tag{1}$$

where W_C is the capture rate and $\lambda = W_D/W_S$ is the ratio of the captured pair dissociation rate to the recombination rate of the singlet pairs. Under the influence of an ac field saturating the magnetic resonance the rate increases to

$$R_{sat} = W_C\left[\frac{1}{1+4\lambda}\right]. \tag{2}$$

The variation of $(R_{sat} - R)/R$ or $\Delta R/R$ is plotted as a function of the ratio λ in Fig. 3. The relative difference in rates reaches a maximum of 0.104 at $\lambda = 0.144$ and is greater than one part in 1000 over a wide range of values. Most published experimental results show a change in recombination rate on the order of 10^{-4} [7,12,14,21–23]. Lower measured EDMR, $\Delta R/R$, amplitudes could be due to a variety of factors including: recombination from triplet pairs, spin-flip from triplet to singlet pairs, incomplete ESR saturation, and other parallel, non-spin-dependent recombination paths. However, Fig. 3 shows that, in theory, the EDMR effect can be quite large under the right conditions.

As a function of the ac field amplitude, B_{ac}, the recombination rate at resonance is given by [24]

$$R = R_{sat}\left[\frac{\gamma^2 B_{ac}^2 T_1 T_2}{4 + \gamma^2 B_{ac}^2 T_1 T_2}\right], \tag{3}$$

in which γ is the gyromagnetic ratio, and T_1 and T_2 are the spin–lattice and spin–spin relaxation times of the captured electrons respectively. Thus, to maximize the EDMR signal, the amplitude of the ac field should be

$$B_{ac} \gg 2/\gamma\sqrt{T_1 T_2}. \tag{4}$$

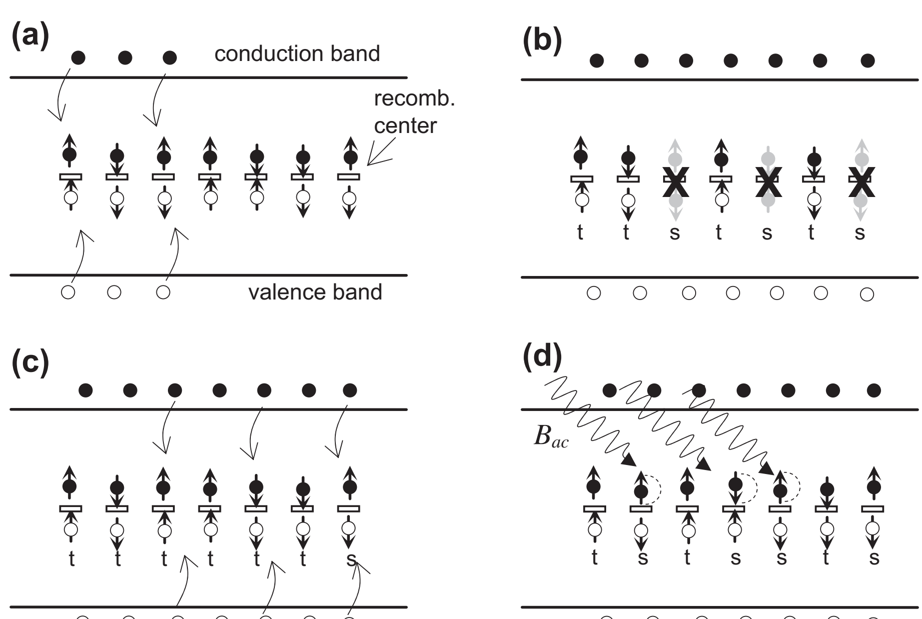

Fig. 2. Illustration of the Kaplan–Solomon–Mott model of spin-dependent recombination: (a) capture of electron–hole pairs in recombination centers; (b) rapid recombination of singlet pairs; (c) accumulation of triplet pairs; (d) increase of singlet pairs and recombination rate by electron spin resonance excitation.