On the shock in samples experiencing transient megagauss fields

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Abstract. Transient megagauss fields with a pulse length of few microseconds interact with
sample material not only by the high field value but also by the extremely high dB/dt of
\( \approx 10^8 \text{T/s} \). A large number of previously unexplained hysteretic phenomena can be attributed
to this fact.

We have investigated the mechanisms for these complications experimentally as well as
theoretically and demonstrate a quantitative analysis for InSb with estimates for the induced
fields, eddy currents, “magneto form” processes and temperature dissipation.

1. Introduction
In cyclotron resonance (CR) experiments in single turn coils on semiconductors various types of
hysteretic phenomena, differences in the absorption in up and down sweeps, have been reported.
The first publications dealt with the spin split electron CR in which the lower field line is
increased in absorption strength in the down sweep at the expense of a decrease of the higher
field line in InAs SQWs and HgSe bulk\([1, 2]\). The overall integrated absorption was conserved
leading to the explanation by a spin lattice relaxation on the timescale of the field pulse \([1, 2]\).

Investigations on e.g bulk HgTe showed an increase of the absorption strength of both spin
split CRs in the down sweeps vs. the up sweep \([3]\). There is an indication that larger conductivity
samples exhibit this behavior rather than the previous one.

The aforementioned effects modify reasonably understood resonances. In bulk InSb, however,
a completely new phenomenon was observed at room temperature. After each zero crossing of
field a resonance drop was observed without a corresponding feature in the down sweeps. \([4]\)
An illustration is given in fig. 1. The absorption strength was found to be dependent on the
field derivative but independent of field magnitude within experimental error. The transmission
drop was not observed in slower pulsed magnets \([5]\) or obscured by tremendous noise in STC-CR
\([5, 6]\). Therefore processes accompanying the field generation must be analyzed carefully to find
the cause for this asymmetry.

2. Eddy Currents and Consequences thereof
The effect of eddy currents in semiconductors exposed to transient magnetic fields can
straightforwardly be calculated from Maxwell’s equations for a thin disc with all dimensions
(radius R, thickness D) well below skin depth \( \delta \) \([7, 8]\). Alternatively the diffusion equation can
be solved for a cylindrical rod of infinite length and radius R to find the induced eddy current
Figure 1. CR trace with the respective magnetic field using nondestructive fields to demonstrate the asymmetric feature as indicated by arrows [4]. The experiment was carried out at room temperature, \( \lambda = 10.59 \mu \text{m} \) and was qualitatively observed in all bulk InSb samples.

density [7, 8]. For \( R \ll \delta \) both cases yield the same result for induced electric fields, current density and secondary processes such as a local temperature rise and a local pressure distribution [8]. The major difference between both cases is found in the magnetic field distribution inside the sample as will be discussed later. The thin disc case is well realized in the CR measurements whereas magnetization measurements favor the use of rod like samples.

Using the conductivity \( \sigma \) in its tensorial form with a Hall like non-diagonal term \( \omega_c \tau \), we obtain in polar coordinates \((r, \phi)\) and a magnetic field \( B(t) \):

- induced electric fields and current density

\[
\vec{E}(r, t) = \frac{r}{2} \frac{dB}{dt}(t) \vec{e}_\phi + \omega_c \tau \frac{r}{2} \frac{dB}{dt}(t) \vec{e}_r, \quad \vec{j}(r, t) = \frac{\sigma r}{2} \frac{dB}{dt}(t) \vec{e}_\phi.
\]

There is a radial electric field due to the finite size of the sample corresponding to a Corbino disc arrangement that can exceed the purely azimuthal field by orders of magnitude for large mobilities. Consequently we determine:

- a temperature rise with the mass density \( \rho \) and the heat capacity \( c_p \) and a pressure distribution similar to flux compression experiments

\[
\Delta T(r, t) = \frac{1}{\rho c_p} \frac{r^2}{16} \int_0^t \sigma \left( \frac{dB}{dt}(t) \right)^2 dt, \quad \vec{p}(r, t) = -\frac{\sigma r^2}{4} \left( \frac{dB}{dt}(t) \right) B(t) \vec{e}_r.
\]

For an initial sweep rate of \( dB/dt \approx 10^8 \text{T/s} \) and a typical \( R \) of 1 \( \text{mm} \) we obtain \( E_\phi \) of order 500 \( \text{V/cm} \) and even larger \( E_r \). For the conductivity dependent quantities we can estimate temperatures of \( \approx 1 - 100 \text{ K} \) and pressure of up to order 10 \( \text{kbars} \) at e.g \( \sigma \approx 2000 \Omega^{-1}\text{cm}^{-1} \).

The influence of the magnitudes of these quantities cannot be assumed negligible. Point (2) may provide an explanation for the hysteresis of HgTe.
3. Experimental Evidence

To verify the influence of eddy current related phenomena we have investigated a rod like sample with megagauss magnetization equipment. The solution of the diffusion equation for a sinusoidal field $H_0 e^{i\omega t}$ acquires the form

$$H_z(r, t) = \frac{J_0(\sqrt{-2i r/\delta})}{J_0(\sqrt{-2i R/\delta})} H_0 e^{i(\omega t)} R^{\delta} \approx H_z(R, t) - \frac{R^2 - r^2}{4 \sigma} \frac{\partial}{\partial t} H_z(R, t)$$  \hspace{1cm} (3)

where $J_0$ is the Bessel-J-Function of order zero and $\delta = \sqrt{2/\omega \mu_0 \sigma}$ the harmonic skin depth.

This result can be used to determine the conductivity directly in megagauss fields using the compensation coil technique with

$$\sigma \frac{d}{dt} B = \frac{8}{W \pi \mu_0 R^4} \int_0^t U_{mag} dt'$$  \hspace{1cm} (4)

where $W$ is the number of windings of the compensation coils and $U_{mag}$ the measured voltage signal. This effect was qualitatively exploited in [9] for SdH measurements in high field.

Applying the derived formulae to an InSb sample that has shown the hysteretic phenomenon we could determine the magnetic field dependent conductivity in megagauss fields. The contribution to the magnetization signal derives from the azimuthal components only and was found not to deviate from the DC case within experimental resolution. We can estimate that the temperature rise and pressure effects are several orders of magnitude smaller than required for such a change of transmission. A trace of the magnetization signal and $\sigma$ is given in fig. 2.

The radial electric field, however, was found to be of order $300 \text{ V/cm}$ at the transmission drop maximum. Using the equation for the change of absorption coefficient ($\Delta K$) as a function of an applied electric field in $\text{V/cm}$ as obtained by [10]

$$\Delta K/K = 126 \times E^2 e^{E/160} \times 5.7 \times 10^{-8}$$  \hspace{1cm} (5)
The observed transmission change is in complete agreement with these data. [10] attributed the transmission change to a generation of carriers by impact ionization and avalanche breakthroughs, causing free carrier absorption. Moreover, the radial electric field is oscillating with the double frequency of the driving magnetic field (1). Thus, the generated carriers move to the sample center whenever B and dB/dt have the same sign as can be seen in fig. 1. They move to the sample boundaries when B and dB/dt have the opposite sign [8]. This is the key mechanism explaining the asymmetric behavior in up and down sweeps. An illustration of the theoretical and measured transmission drop for the up sweep is given in fig. 3.

4. Conclusion
Eddy currents are not a minor perturbation to the data obtained in semiconductors exposed to a transient field, but can modify existing resonances. Contributions of eddy currents have been studied on InSb quantitatively but were correspondingly observed in almost all other materials investigated. The influence scales with the sample proportions and its conductivity. Thus reducing sample dimensions or avoiding large electrically connected areas lead the way to avoid this problem. In general, one has to consider eddy currents in all semiconductor experiments using transient magnetic fields.

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