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To cite this article: M von Ortenberg 2006 J. Phys.: Conf. Ser. 51 371

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Abstract. A review of experiments on semiconductors in high magnetic fields is presented with special emphasis on transient megagauss fields generated by the single-turn coil and explosive flux-compression. Both, techniques of field generation and the special consequences of transient magnetic fields on the sample system will be discussed thoroughly. In detail several magneto-transmission experiments using 10.6 μm wavelength radiation on bulk and nanostructured semiconductors will be presented in addition to special features of magnetization behavior.

1. Introduction

Present day life of human society depends increasingly on sophisticated sensor and communication technology. Without suitable semiconductor materials involving charge and spin sensitive electric currents these technologies would not be possible. The most important prerequisite for the technological application is the most comprehensive knowledge of the charge-carrier parameters including spin of these materials. One of the most efficient experimental methods for this characterization is the magneto-spectroscopy. It provides detailed information on the static and dynamic parameters as mass, lifetime, charge, and spin polarization. The higher the applied external field the more comprehensive is the characterization. In this way high-magnetic-field technology was stimulated tremendously.

In contrast to the electric field the effect of an external magnetic field on charge carriers results in classical physics in an isoenergetic modification of the state of motion without additional energy dissipation, since the Lorentz force is always perpendicular to the direction of motion. In this way the motion parameters of the charge carriers can be studied as a function of the externally tunable magnetic field. In quantum mechanics we have an reorganization of the states and quantum numbers and the isoenergetic quality holds only in the average with an uncertainty of $\Delta E = \hbar \omega_c$, the cyclotron energy.

2. Historical remarks

Shubnikov and de Haas [1] were the first pioneers to demonstrate the efficiency of strong magnetic field in the investigation of the electronic properties of solids by studying the magneto-resistance of Bi. The first magneto-resonance experiments on semiconductors were performed much later nearly simultaneously by the groups of Kittel C [2] and Lax B [3]. Using microwaves in only some hundreds of Gauss it was possible to prove that the holes in Ge had anisotropic mass properties corresponding to the crystal symmetry. These key-experiments defined the start of modern magneto-spectroscopy.
Nearly always the progress in high-magnetic-field generation resulted also in new scientific highlights in solid-state physics, so that longing for magnetic fields even in the multi-megagauss range became a driving force. Many scientific results honored by the Nobel prize are directly related to the increase of the feasible magnetic field range at the time.

3. The crystalline solid in the presence of an external magnetic fields

In classical physics the effect of an external magnetic field $B$ manifests by the Lorentz force on a carrier bearing the charge $-e$ and having the velocity $v$:

$$\frac{dp}{dt} = -e(v \times B)$$  \hspace{1cm} (1)$$

To obtain this result also in the classical limit of quantum mechanics we have to substitute in this theory the canonical momentum $p$ by the kinetic momentum including the vector potential $A$:

$$\pi = p + eA$$  \hspace{1cm} (2)$$

The relation between external magnetic field $B$ and the vector potential $A$ is:

$$B = \text{rot } (A)$$  \hspace{1cm} (3)$$

Since B is not changed for a gauge transformation

$$A \rightarrow A + \text{grad}(\Phi)$$  \hspace{1cm} (4)$$

there is an infinite variety of gauge transformations leading all to exactly the same physical observables. For the observable of the energy this implies the possibility of a corresponding large energy degeneracy manifesting finally in a well structured density of states for the quasi-free electrons in the presence of an external magnetic field representing the different Landau subbands.

The magnetic field couples, however, not only to the angular momentum, but also to the intrinsic magnetic moment $\mu$ of the electrons and hence to the spin $s$:

$$\hbar \frac{ds}{dt} = \mu \times B = -g\mu_{\text{Bohr}}s \times B$$  \hspace{1cm} (5)$$

giving rise to many additional lifting of degeneracies. A special feature is the coupling of spin and orbital angular momentum as relativistic effect. Please note, that equ. 1 and equ. 5 are of the same mathematical and topological structure and can be written as:

$$\frac{dk}{dt} = -e(k \times B) \cdot m^{-1} \text{ and } \frac{ds}{dt} = -g\mu_{\text{Bohr}}(s \times B) \cdot \hbar^{-1}$$  \hspace{1cm} (6)$$

where the momentum has been expressed by $p = \hbar k$. Both equations of motion describe vectors rotating with one end point around the vector of the magnetic field $B$, while the other one is fixed. The angular frequencies are $\omega_k = eB/m$ and $\omega_s = g\mu_{\text{Bohr}}/\hbar$ for $k$ and $s$, respectively.

In a periodic solid the $E(k)$-relation determines the electronic energy levels. In the Peierls approximation [4] the $k$-vector is substituted by $\pi/\hbar$ in the corresponding matrix of the Hamiltonian. This results in an effective quantization of:

$$(k_x^2 + k_y^2) = (2N+1)\lambda^2 = (2N+1)eB \cdot \hbar^{-1} \text{ for } N = 0, 1, 2, \ldots$$  \hspace{1cm} (7)$$

where the magnetic length $\lambda$ is given by:
\[ \lambda^2 = \hbar \cdot (eB)^{-1} \]  

(8)

For \( B = 100 \, \text{T} \) the magnetic length \( \lambda = 2.56 \, \text{nm} \).

It is quite evident that with increasing magnetic field \( B \) the \( E(k) \)-relation of the electrons can be probed in a more extended way. Hence for \( 100 \, \text{T} \) and \( N=0 \) about 20\% of the Brillouin zone of a material with a lattice constant of 0.5 nm is included into the investigation.

The quality of the magnetic length \( \lambda \) as a tunable length measure is of special interest in *nano*physics. Any potential structure in this regime can be probed by this measure, especially the dimensions of quantum wells, quantum wires, and quantum dots [5].

4. High-magnetic-field generation

In principle the generation of a magnetic field is straightforward: any electric current produces in its vicinity a magnetic field. The most simple realization of a field generator is a coil of a metal conductor. To increase the resulting field only an increase of the current density is necessary. This increase, however, has its technical limitation by two effects: whereas the energy dissipation within the coil can be overcome by cooling or be prevented by superconducting wire materials, the second barrier manifests in the magnetic pressure within the coil originated by the Lorentz force acting on the wire elements in the magnetic field. This force produces at 100 T a pressure of about 40 to/cm\(^2\) and has to be balanced either in a static or dynamical way. It is evident that presently there are no materials to withstand a pressure of 40 ton/cm\(^2\) continuously. Even for pulsed magnetic fields a short-time pressure of only about 26 to/cm\(^2\) can be balanced corresponding to peak fields of 80 T for *non-destructive* coils [6]. So far the production of megagauss fields is unavoidably connected with dynamical forces related to *semi-destructive* and *destructive* coils.

The most simple setup is the *single-turn coil* [7]. Here the Lorentz force is simply balanced by the inertia of the explosion of the coil material in radial outward direction. This means that despite the explosion of the coil any equipment inside the coils is not harmed. Therefore this coil type is attributed to be *semi-destructive*. Since the resulting magnetic field decreases rapidly with expansion of the coil, the experiment should be finished before the coil radius had time to increase. That is why the actual pulse time is only of the order of microseconds.

In the method of *flux compression* the Lorentz force is not only balanced but an external dynamical force, but overcompensated so that the coil does not *explode* but *implode*. In this way coil and equipment inside the coil are destroyed, this means the coil is characterized to be *destructive*. The force for the implosion can be generated by the radial high-velocity impact of matter, which has been accelerated either by electromagnetic means, *electromagnetic flux compression* [8], or the *explosive flux compression* [9] using TNT or other explosive charges. The *explosive flux compression* provides for experimental use peak fields higher than 1000 T. The absolute peak field without experimental application other than field measurement obtained so far is 2,800 T [10].

4.1. *Non-destructive pulsed submegagauss coils*. For the generation of magnetic fields beyond the critical field \( B_c \) of superconducting solenoids only conventional coils can be used with large energy dissipation. To limit the adiabatic warming up of the coil only pulsed operation with typical pulse times between 1 msec and 1 sec are possible. To withstand the Lorentz stress sophisticated armaments are necessary, so that at present 80 T peak fields have been obtained [6]. It should be worth mentioning that these orders of pulse length is still allowing many experimental measurements, which cannot be performed at shorter pulses, i.e. magneto resistance measurements. Most of the experimental setups producing high magnetic fields have decided to apply this method as basic method for their field generation. It balances efficiency with financial investment and scientific output.

4.2. *The single-turn coil*. The single-turn coil represents a coil consisting of only one winding. It was conceived by Forster and Martin [11] and later modified into a scientific instruments by Herlach and McBroom [11]. Presently the Berlinian setup [7] can produce peak fields of 331 T in a coil of 3 mm
diameter in connection with a 225 kJ/60 kV capacitor bank as energy source and hence reaches worldwide the highest fields produced by this technique as shown in figure 1. The features of high megagauss fields and characteristic pulse parameters of only some microseconds makes the semidestructive single-turn coil to an valuable device also to study transient magnetic effects. The combination of data obtained in both, up- and down-sweep allows the study of hysteresis effects and their physical mechanism in the data.

4.3. Destructive flux-compression. In the flux-compression a short-circuited single-turn coil - the so called liner – is radially compressed, so that the magnetic flux kept inside is concentrated. This method transforms essentially the kinetic energy of the liner material into magnetic energy. Depending on the method of the initial liner acceleration we distinguish between electromagnetic and explosive flux-compression. In the first method the liner is compressed by an external magnetic field, the latter by a concentric inward directed explosion as used for triggering the atomic bomb. The advantage of this method is the fact that it provides the highest magnetic fields possible for any experiment. The disadvantage is, that the field calibration is extremely demanding, since only one up-sweep exists without down-sweep.

Figure 1 Pulse structure and peak fields of the single-turn coil equipment in Berlin.

Figure 2 The Shubnikov-de Hass oscillations on bulk HgSe:Fe imaging directly the spin-split density of states at the Fermi surface [12].
5. Magneto-transport
The most impressive manifestation of the magnetic field dependent density of states in the presence of an external magnetic field is found in the transverse magneto-resistance, as demonstrated in figure 2 for HgSe:Fe [12]. Due to the extremely high mobility the data depict directly the spin-split density of states at the Fermi energy as a function of the magnetic field. Thus the characteristic \((E-E_F)^{0.5}\) functional dependence of the different Landau level characterized by the quantum number \(N\) can be seen. In this experiment a direct comparison of the cyclotron energy \(\hbar \omega_c = \hbar eB/m^*\) and the Fermi energy \(E_F\) by non-resonant magneto-spectroscopy is performed.

In figure 3 we have reproduced the corresponding data for a Q2D-sample of the same material having a \(\text{comb}\) structure and compare the data with the theoretical simulation [13]. The nearly perfect agreement confirms the high degree of understanding of the system. In this way magneto-transport provides detailed knowledge on electronic levels in solid state.

![Graph of Experimental data and simulation on the Shubnikov-de Haas oscillations on a HgSe/HgSe:Fe super lattice](image)

Figure 3  Experimental data and simulation on the Shubnikov-de Haas oscillations on a HgSe/HgSe:Fe super lattice [13].

6. Infrared magneto-spectroscopy
Optical magneto-spectroscopy is mostly \textit{resonance-spectroscopy}. Only in rare experimental situations also non-resonant spectroscopy based on magnetic-field-induced phase-transitions is possible. In resonance-spectroscopy there is a direct comparison of the radiation energy \(\hbar \omega\) and the energy separation \(\Delta E\) of two magnetic-field-dependent levels with allowed optical transition. The most prominent resonance of this type is the cyclotron resonance between two adjacent Landau-levels. In figure 4 we have reproduced the magneto-transmission spectra of 10.6 \(\mu\)m-wavelength radiation through pure HgSe for different temperatures as a function of the magnetic field in the megagauss range as obtained by use of the \textit{single-turn coil} [14]. At low temperatures the cyclotron resonance (CR) is hardly detectable, so that the spectrum is dominated by interband transitions in the zero-gap material. With increasing temperature the spin-split cyclotron resonance increases in intensity and suppresses all other transitions. In figure 4 the data are plotted for up- and down-sweep of the magnetic field pulse. Whereas the resonance transition remains unchanged for up- and down sweep, there is a pronounced change in the resonance intensity. This indicates hysteresis effects and will be discussed in detail in chapter 7. Despite the rather wide range of the \textit{single-turn coil}-generator to cover
several megagauss the data so obtained include sometimes the request for even higher fields. A typical example for such a situation is the magneto-optical investigation of cubic GaN [15]. The measurements obtained in Berlin with the single-turn coil up to 270 T clearly indicate an additional high-field absorption, which could not completely be resolved due to the field limitation. Since the single-turn coil method is semi-destructive the sample was not harmed during the experiment and could be used in an explosive flux-compression experiment up to 700 T. The resulting data of both experiments are included in Fig.5, where we have plotted both data as a function of the magnetic field. The high-field data beyond 270 T show clearly that the single-turn coil data were probing an additional resonance, which could not be resolved within the “low-field”-measurements of this method. It is worth being noticed that the data obtained with the two totally different generators agree perfectly.
The explosive flux compression can be pushed even to higher fields for experiments than just demonstrated. We have investigated n-type GaAs in magnetic fields up to 1000 T as shown in figure 6. Here the transmission of 10.6 μm radiation through GaAs at room temperature is plotted as a function of the magnetic field [16]. Whereas the low-field resonance is well identified as the cyclotron resonance of electrons in the vicinity of the Γ-point, the transmission drop at 550 T has to be attributed to electrons at the L-point: due to the small effective mass of the Γ-electrons the corresponding lowest Landau level crosses at high magnetic fields the L-levels, so that these states become populated and contribute by resonance transitions.

7. Transient effects

So far the presented experimental results were mostly obtained in thermodynamic equilibrium, involving that the relaxation times of the system are short with respect to the characteristic times of the magnetic field variation. This is, however, not always justified. Since the characteristic time parameters of the field variation are in the order of μsec any relaxation time τ of this order of magnitude should produce detectable hysteresis effects with respect to up and down sweep of the field, since the thermodynamic equilibrium state is not reached any during the pulse sweep. The second effect caused by rapidly varying “transient” magnetic fields has its origin in the large electric fields induced by dB/dt ≈ 10⁸ T/sec. We give an example for both aspects.

7.1. Time dependent population effects. In figure 4 we have reproduced the measurements of the spin-split cyclotron resonance in HgSe for different temperatures as a function of the magnetic field for up- and down-sweep [14]. Especially at high temperatures the two cyclotron resonance lines exhibit a pronounced change in intensity for up- and down-sweep, while the resonance position remains unchanged. This phenomenon is easily explained by the retarded time development of the population of the initial level. This can be described in the following way using the actual non-equilibrium population probability f(E) and the equilibrium function f₀(E):

\[
\frac{df(E)}{dt} = - \frac{(f(E)-f_0(E))}{\tau}
\]  

(9)

Figure 7 The transmission data in the lower part show clearly (arrows) unexpected drops only in the up-sweeps. These phenomena occur only for \(B \cdot dB/dt > 0\) as can be seen in comparison with the field data [17].
where we have introduced the relaxation time $\tau$ of the spin states. It should be noted that the energy $E$ is time dependent via the time dependence of the applied magnetic field $E(t) = E(B(t))$. The evaluation of this model results in a spin-lattice relaxation time in HgSe of $\tau = 1.2 \mu$sec for megagauss fields [14].

7.2. Space and time dependent population effects. A completely different type of hysteresis was observed in InSb in transient magnetic fields as shown in figure 7: a pronounced transmission drop occurs always at the beginning of the half-sine shaped magnetic field pulse independent of the field direction [17]. The existence of this reproducible transmission drop evidently occurs only for $B \cdot dB/dt > 0$, which can be interpreted in that way, that the observed effect is related to the direction of the Lorentz force on the induced eddy currents within the conductive sample driving the charge carrier towards the centre. For the down-sweep, however, the carrier are driven to the outer edge of the sample, where they cannot interact with the infrared radiation.

8. Summary
The two different features of present days megagauss fields, namely high amplitude of the field vector as well the transient character of the field due to the short-pulse operation of the generators available, provide useful tools to provide essential information on both, energy levels and dynamics of electrons in semiconductors.

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