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Author(s):

**Laurence J. Campbell, MST-10
Alex H. Lacerda, Florida State Univ.
Yongmin Kim, Northeastern Univ.
Dwight G. Rickel, DX-6**

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Advanced Measurements and Techniques in High Magnetic Fields

Laurence J. Campbell*, Alex H. Lacerda (Florida State University),
Yongmin Kim (Northeastern University), Dwight G. Rickel

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). High magnetic fields present a unique environment for studying the electronic structure of materials. Two classes of materials were chosen for experiments at the National High Magnetic Field Laboratory at Los Alamos: highly correlated electron systems and semiconductors. Magnetotransport and thermodynamic experiments were performed on the renormalized ground states of highly correlated electron systems (such as heavy fermion materials and Kondo insulators) in the presence of magnetic fields that are large enough to disrupt the many-body correlations. A variety of optical measurements in high magnetic fields were performed on semiconductor heterostructures including GaAs/AlGaAs single heterojunctions (HEMT structure), coupled double quantum wells (CDQW), asymmetric coupled double quantum wells (ACDQW), multiple quantum wells and a CdTe single crystal thin film.

1. Background and Research Objectives

The motivation for this work was to demonstrate the research potential of the recently established National High Magnetic Field Laboratory (NHMFL) at Los Alamos. This general user facility provides high magnetic fields and associated instrumentation for researchers from universities, industry, and government laboratories. The primary application of these fields is to study materials such as alloys, semiconductors, organic conductors, and highly correlated electron systems including superconductors and heavy fermion compounds. We investigated some examples of highly correlated electron systems and semiconductors.

Strongly correlated electronic systems include a wide family of materials for which the many-body interactions among the electrons and ions lead to behavior far removed from simple single-particle descriptions for simple metals and dielectrics. Among the strongly correlated systems are heavy fermion compounds, intermediate-valence compounds,

* Principal Investigator; e-mail: LJC@lanl.gov .

Kondo insulators, and much of superconductivity phenomena, especially in the high temperature superconductors. The ground state of these systems is quite complicated and high magnetic fields offer a special tool which, in a valuable way, 'decomposes' the complexity of this ground state and frequently leads to experimental results that reveal the nature of the ground state.

Specialized probes were developed to measure magnetotransport, magnetization, and magnetostriction of the following systems:

- Heavy fermion materials (Yb-based compounds; Ce-based compounds, such as CeB₆; U-intermetallic compounds, such as UNiGe, UNiAl). The first measurements of the quadrupole-antiferromagnetic line as a function of magnetic field are an important goal.
- Normal phase of HTC superconductors (La and Sr - CuO₄)
- Kondo insulators (especially, small gap semiconductors, SmB₆, FeSi, Ce₃Bi₄Pt₃)

Semiconductor behavior is marked by the rich environment where the carriers reside. Modern methods of epitaxial growth such as molecular beam epitaxy and metal organic chemical vapor deposition provide the capability of fabricating a wide variety of thin (5-100 Angstrom) epitaxial layers of semiconductor compounds on different substrates with interfaces of atomic precision. In the formation of such heterostructures, the layers may be of different composition or doping or a combination of both. Semiconductor heterostructures are particularly unique as they provide a system for studying two-dimensional physics as well as having many opto-electronic device applications. These systems can be separated into two classes: quantum wells and superlattices.

We made magneto-photoluminescence and magneto-transport measurements to study the electronic band structures of various types of undoped and doped semiconductor heterostructures in the presence of strong magnetic fields up to 65 tesla. The magnets used for these studies include a 20 T superconducting magnet and 50-65 T capacitor-driven magnets having a pulse length of 15 ms. The measurements on heavy fermions and Kondo insulators took advantage of dilution refrigerators now available for these magnets to reach temperatures below 30 mK. Many measurements reached extreme combinations of high field and low temperature hitherto unattainable.

2. Importance to LANL's Science and Technology Base and National R&D Needs:

The National Science Foundation has funded a component of the National High Magnetic Field Laboratory (NHMFL) at LANL to produce pulsed magnetic fields for research by general users from universities, industry, and government laboratories. This is the first pulsed field user facility in the US and the studies carried out in its various magnets

advance basic research and technology development in a wide range of materials including semiconductors, alloys, organics, and high temperature superconductors. Thanks to unique power generation capability at LANL, the NHMFL is able to provide magnetic fields of a strength and duration unmatched anywhere in the world. In addition, the NHMFL interfaces with existing LANL programs that produce high magnetic fields by explosive flux compression, thereby making these types of fields available to general researchers for the first time. Over 80 scientists and students came to Los Alamos to perform experiments at NHMFL in the past year.

The strong justification for the accommodation of NHMFL at LANL is the the importance of high magnetic fields for materials science. Among the broad areas of materials research where high magnetic fields are crucial are correlated electron systems (superconductivity, Kondo systems, heavy fermion materials), organic conductors, semiconductors, and alloys. In addition, high magnetic fields have shown their importance for materials processing and in providing the foundation for specific probes, such as magnetic resonance.

The NHMFL at Los Alamos will likely be unsurpassed for several years in its capacity to furnish the highest pulsed fields to materials science researchers. The existence of this laboratory will not only provide a powerful tool for materials science at Los Alamos, but will also attract outside users and collaborators, both directly relevant to the maintenance and strengthening of core competencies in complex experimentation and measurements and materials science and solid state physics.

The two research topics chosen for this LDRD project, both at the forefront of research, were chosen to illustrate the types of results that high magnetic fields can produce.

3. Scientific Approach and Accomplishments

Correlated Electrons Study

Ground state properties of heavy fermion compounds in high magnetic fields.

Compounds that exhibit magnetic field induced transitions were the primary focus. In particular, $\text{YbNi}_2\text{B}_2\text{C}$ is a new heavy fermion compound presenting extremely high magnetic anisotropy. Experiments on this compound revealed the possibility of having metamagnetic transitions in magnetic fields to 100 T.

Unconventional semiconductors in high magnetic fields.

The object of this study was the energy gap formations of Kondo insulator compounds, in particular, the effect of very high magnetic fields on the energy gap formation of SmB_6 materials. Magnetoresistance experiments were performed in magnetic fields to 50 T and temperatures down to 40 mK. The low excitation gap is seen to close for the first time in a magnetic field of 35 T at 40 mK. More detailed studies of sample dependence and theoretical interpretation of this effect were carried out.

Optics of Semiconductors Study

A variety of optical measurements revealed the behavior of semiconductor heterostructures in high magnetic fields including GaAs/AlGaAs single heterojunction (HEMT structure), coupled double quantum wells (CDQW), asymmetric coupled double quantum wells (ACDQW), multiple quantum wells and CdTe single crystal thin films.

Magneto-photoluminescence (MPL) intensity and energy oscillations and optical Shubnikov-de Haas (OSdH) oscillations in a modulation doped GaAs/AlGaAs single heterojunction (with C.H. Perry, Northeastern University, Boston, K-S. Lee, ETRI, Korea, D.G. Rickel, NHMFL-LANL).

In the presence of magnetic fields, the electron energy levels are quantized into Landau levels. With increasing field, Landau levels cross the Fermi energy. During this process, electrons transfer from higher Landau levels into the lower Landau levels leading to many interesting features such as the integer quantum Hall effect (IQHE). A single heterojunction is often called a high electron mobility transistor (HEMT). We measured MPL of such a modulation doped single heterojunction. Energy and intensity oscillations are observed. Energy maxima correspond to intensity minima; this oscillatory behavior is caused by the interaction (crossing) between Landau levels and the Fermi level.

Due to the low doping density in our sample, electrons occupy only the first sub-band and the Fermi energy lies below the second sub-band under no illumination. However, laser excitation produces photo generated electrons which move into the well providing partial occupation of the second sub-band. We believe that the energy and intensity oscillations in the MPL spectra are associated with the interaction between the second sub-band Landau levels occupied by photo-generated electrons and the Fermi energy. To verify this, we also have performed OSdH measurement. When the Landau levels cross the Fermi energy the magneto resistance undergoes Shubnikov de-Haas (SdH) oscillations. The sample was illuminated under the same conditions as the MPL studies while measuring the magneto resistance. The result provides so called optical Shubnikov

de-Haas oscillations. The measured OSdH oscillations are in excellent agreement with our MPL oscillations.

MPL measurement of GaAs/AlGaAs double-well structures.

a) Modulation Doped Coupled Double Quantum Well (CDQW) (with J. Simmons and K. Klem, Sandia National Laboratory). It is from problems in well known basic quantum mechanics that CDQWs form two energy levels corresponding to symmetric and antisymmetric states. According to recent theoretical studies [1], the two-wave vector dispersion curves for each well 'anticross' in the k-space in the presence of an in-plane magnetic field applied perpendicular to the quantum well growth direction (z-axis). With increasing magnetic field, the Fermi level moves down and when it intersects the anticrossing point, the density of state (DOS) diverges due to a van Hove singularity that occurs at this saddle point.

We measured the MPL of a modulation doped CDQW both in the direction parallel and perpendicular to the z-axis. We attempted to investigate the divergence of the DOS with an in-plane magnetic field but could see no singularity in the MPL measurement. We believe that this is mainly due to the PL recombination process. PL recombination occurs mostly at $k=0$, i.e., between the bottom of the conduction band and the top of the valence band; however the singularity occurs at the Fermi level. Further investigations such as photoluminescence excitation (PLE) or photo-reflectance are needed. In fields applied perpendicular to the CDQW plane, we saw anomalous effects in the MPL spectra. Interactions between symmetric and antisymmetric states and magneto-polaron effects are thought to be directly related to these MPL anomalies.

b) Asymmetric Coupled Double Quantum Well (ACDQW). For an undoped ACDQW, we found that the PL intensity changes drastically with excitation wavelength and power. We observe an additional PL peak about 1.2 meV below the main electron-heavy hole exciton peak. With 488 nm Ar ion laser excitation, the intensity of this additional peak increases linearly whereas the intensity of the main exciton peak saturates with increasing laser power. Excitation using a 708 nm Ti:S laser produces PL intensities which behave in an opposite way to those observed with 488 nm laser excitation. High energy excitation can create a negatively charged exciton called a trion analogous to the negatively charged hydrogen atom. The intensity and energy variation with magnetic field are considered to be directly related to the creation of such excitations.

GaAs/AlGaAs undoped multiple quantum wells (with K-S. Lee, ETRI, Korea).

We performed a series of MPL investigations of bi-exciton states in GaAs/AlGaAs quantum wells having well widths of 15, 20, and 25 nm. The low temperature ($T = 4.2$ K) PL studies of the heavy-hole exciton and the bi-exciton peaks showed linear and superlinear increase in intensity with the excitation density, respectively. The bi-exciton binding energy at zero field was determined to be 1.17 meV for all the quantum wells investigated in this study. In the presence of a magnetic field applied parallel to the growth axis (z-direction), the MPL bi-exciton peak intensity decreased with increasing magnetic field. The diamagnetic shift of the bi-exciton was clearly observed up to $B = 9$ T; at higher fields it was not possible to clearly resolve the heavy-hole excitons and bi-excitons in our experiments. We find that the bi-exciton binding energy linearly decreases at the rate of 0.079 meV/T. A linear extrapolation of these results to higher fields indicates that bi-excitons in GaAs/(Al,Ga)As quantum wells are frozen out at $B > 15$ T.

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Figure 1. Resistance of SmB_6 as a function of applied magnetic field at 40 mK.

Figure 2. Low temperature magnetoresistance of $\text{YbNi}_2\text{B}_2\text{C}$ for field perpendicular to the c axis as a function of applied magnetic field.

Figure 3. The temperature dependence of the electrical resistivity of CeBe_{13} at various pressures.

Figure 4. Excitation power dependence of Shubnikov-de Haas oscillations for sample GEN552 single heterojunction at $T = 2\text{K}$. Laser excitation of wavelength 514.5 nm (2.4 eV) was introduced to the sample for 2 ms with different levels of laser power.

Figure 5. Magnetic field dependence of the photoluminescence (PL) intensity, electron density and optical Shubnikov-de Haas (OSdH) oscillations at $T = 4$ K. In this figure the OSdH minima correspond to electron density and PL intensity maxima.

Figure 6. Sample 'B' in pulsed magnetic fields (B parallel to plane) at $T = 77$ K. In (a) both the e1-hh1 and the e2-lh2 transitions are resolved at $B = 0$ T. The e2-lh2 transition is denoted by square markers in (b). With increasing field these transition energies converge and may anticross at fields above 50 T.