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Ferromagnetic Semiconductors

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Annotation. Semiconductors and ferromagnets play complementary roles in current information technology. On the one hand, low carrier densities in semiconductors facilitate modulation of electronic transport properties by doping or external gates. Information processing is, therefore, most commonly based on semiconductor devices. On the other hand, because of long-range order in ferromagnets only small magnetic fields are necessary to reorient large magnetic moments and induce large changes in magnetic and transport properties. This explains the use of ferromagnetic metals in storage devices.

Key words: ferromagnet, magnetic, metal, speed memory, temperature.

Introduction: Existing semiconductor electronic and photonic devices utilize the charge on electrons and holes in order to perform their specific functionality such as signal processing or light emission. The relatively new field of semiconductor spintronics seeks, in addition, to exploit the spin of charge carriers in new generations of transistors, lasers and integrated magnetic sensors. The ability to control of spin injection, transport and detection leads to the potential for new classes of ultra-low power, high speed memory, logic and photonic devices. The utility of such devices depends on the availability of materials with practical (>300 K) magnetic ordering temperatures. The critical behavior in the proximity of the Curie temperature is still one of the central problems in the physics of itinerant ferromagnets. By establishing the universality class for the phase transition, one can obtain information on the range of the exchange interactions determining magnetic order in the system in question. One can then use this information to distinguish between long-range exchange interactions (such as in the mean-field approximation) or short-range interactions (as in the case of the Heisenberg or Ising models).

Aim and tasks the research. Thesis understands resistivity behavior of GaMnAs at the near Curie temperature and critical behaviors of the specific heat of GaMnAs.

- Determining the resistivity of sample by Van der Pauw method;
- Analyzing critical behavior of resistivity;

Research Method and Technique. Methods used are Van der Pauw and Superconducting quantum interfernce device methods.

The ferromagnetic semiconductor Ga_{1-x} Mn_xAs has been studied intensely over the last decades and has become a model system for diluted ferromagnetic semiconductors [1]. It is now widely accepted that the ferromagnetism in Ga_{1-x} Mn_xAs arises from hole-mediated exchange interaction between the local magnetic moments of the Mn, and the mean-field-like Zener model has been widely used to describe this system [2]. The critical behavior in the vicinity of the Curie temperature is one of the central problems in the physics of semiconducting ferromagnets. By establishing the universality class for the phase transition, one can obtain information on the range of the exchange interactions determining magnetic order in the system in question. One can then use this information to distinguish between long-range exchange interactions (such as apply in the mean-field approximation) or short-range interactions (as in the case of the Heisenberg or Ising models). In this work, we present the results of experimental study of the critical behavior of the specific heat for $Ga_{1-x} Mn_xAs$ with low concentration of Mn. The $Ga_{1-x} Mn_xAs$ layers with low Mn concentration (x < 0.03) were grown on semi-insulating (001) GaAs substrates by using MBE. The epilayers with thickness about 1μm were grown at low temperature of 270 ^{0}C. The Mn concentration in the layers was estimated from x-ray diffraction measurements and it was additionally confirmed by x-ray microanalysis. No post-growth thermal annealing was performed. The specific heat was measured by using the photothermal method described elsewhere [3].The back side of the sample was kept in thermal contact with a thin $LiTaO_3$ pyroelectric transducer. The front sample surface was blackened with a thin layer of carbon black, and was heated by an optically modulated He–Ne laser. The modulation frequency was about 3 kHz. At this frequency, the thermal diffusion length is much smaller than the total thickness of the samples (GaMnAs film+GaAs substrate;~300 μm). This ensures that the investigated samples were thermally thick. The photopyroelectric signal phase was detected by a lock-in amplifier. The sample thermal diffusivity was then calculated by using the total signal phase shift. Figure 3.2.1 shows the temperature dependence of the magnetic specific heat ΔCm for the investigated sample, which was obtained by subtracting the smooth background of the specific heat of the GaAs substrate. The nonmagnetic contribution of the GaMnAs layers to the specific heat is supposed to be very close to the specific heat of the GaAs because the Mn concentration in the samples investigated is relatively low.

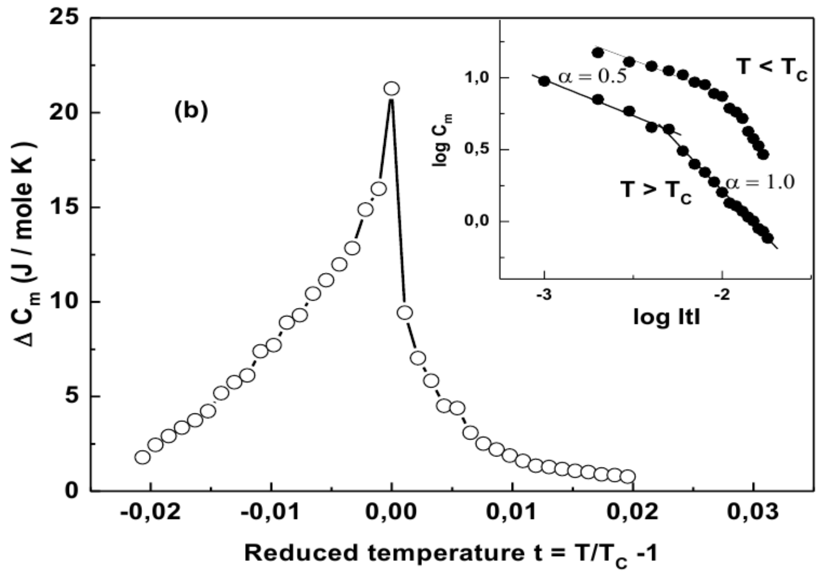

Figure 3.2.1 The magnetic specific heat of the $Ga_{0.0974}Mn_{0.026}As$ sample. Inset: the magnetic specific heat versus the reduced temperature using a double logarithmic scale.

The critical behavior of the specific heat near the phase transition is described by $C_p = C^{\pm}t^{-\alpha}$, where $C^{\pm}$ are the amplitudes of the specific heat above (+) and below (-) T_c, t = T/T_c-1 is the reduced temperature and and α is the critical exponent of the specific heat [4]. It is seen from Fig. 1, that for the $10^{-3} < t < 10^{-2}$ regarding the reduced temperature interval close to the T_c, the experimental data above and below T_c have a similar slope of about α = 0.5. Such kind value is observed in the case of the mean-field critical behavior, including the three-dimensional (3D) Gaussian fluctuations. The contribution of Gaussian fluctuations to the specific heat is given by ΔC = $C^{\pm}t^{-\alpha}$, where α = 2 – d/2, and d is the dimensionality. The amplitude ratio $C^+ / C^- = n/2^{d/2}$ where n is the number of spin components [5]. The value of C^+/ C^- =0.37, determined from this experimental plot, is close to the theoretical value of 0.35 for n=1, which shows the presence of a strong magnetic anisotropy in the GaMnAs samples. With increasing temperature the crossover from 3D to two-dimensional (2D) mean-field-like behavior α =1.0 was observed as the temperature moves away from the critical point. The critical behavior of a system exhibiting a second order phase transition is strongly affected by the range of interactions. In the limit of infinite interactions, the system is characterized by the mean-field scaling behavior.

However, according to the well-known Ginzburg criterion [6] the mean-field-like behavior occurs even for finite interaction ranges, sufficiently far away from the critical temperature.

Practical importance and implementation of research results. Specific heat was used to study the magnetic phase transition in GaMnAs. Two types of samples were investigated. The sample with a Mn concentration of 1.6% shows an insulating behavior whereas the sample with a Mn concentration of 2.6% is metallic. The temperature dependence of the specific heat for both samples reveals a lambda-shaped peak near the Curie temperature, which indicates a second-order phase transition is occuring in these samples. The critical behavior of the specific heat for the GaMnAs samples is consistent with the mean-field behavior with Gaussian fluctuations of the magnetization in the vicinity of T_c.

Summary: In summary, the critical behavior of GaMnAs near the Curie temperature was experimentally studied by using the temperature dependencies of the resistivity, the specific heat, and the magnetization of GaMnAs. It is shown that, for large Fermi wave vector, the maximum of $d\rho/dT$ matches with the Curie temperature. Nevertheless, the Fisher-Langer type critical behavior $d\rho/dT \infty\ C$ is not observed due to the very low value of the Ginzburg temperature in GaMnAs. For low free carrier concentration the Curie temperature coincides with the resistivity maximum and the de-Gennes – Friedel critical behavior is observed.

The magnetic specific heat for $T > T_C$ demonstrates the crossover from the one dimensional to the three dimensional critical behavior when temperature become closer to the Curie temperature. This is explained by the existence of Mn-Mn dimers oriented along one direction at the beginning of the formation of the ferromagnetic phase on the paramagnetic side of the phase transition.

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