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Evaluation of the PhD Dissertation
"Preparation and characterization of ferromagnetic GaMnAs epilayes",
by Mr. Kamil Olejník

The presented Dissertation is a summary of the experimental work of Mr. Kamil Olejník on the epitaxial growth and characterization of GaMnAs. This ferromagnetic semiconductor is one of the most important emergent materials. The unique combination of semiconducting and ferromagnetic properties makes GaMnAs a primary material candidate for spintronic devices which will offer novel functionalities---coming from the non-volatility of the ferromagnetic order, electrical control of the ferromagnetism, and magnetic control over electric currents---to the existing charge-based semiconductor electronics. No wonder that many groups worldwide have undertaken the challenge of producing high quality, high-Curie temperature GaMnAs samples. The Prague group of the Institute of Physics of the Academy of Sciences, at which the work of the presented Dissertation was based, is a world leader in these efforts. The group has made GaMnAs of the highest Curie temperature by fine tuning the epitaxial growth technology for this material. The Dissertation is a timely and important contribution to the field of spintronics in general, and to materials science in general.

The most important achievement reported in the Dissertation is inventing technological recipes for making high quality GaMnAs. Placing Mn impurities into GaAs beyond the equilibrium solubility limit of about 0.1% is possible by non-equilibrium growth techniques, in particular by molecular beam epitaxy (MBE). What makes GaMnAs ferromagnetic is the Mn atoms substituting Ga. In the growth process, however, Mn also go to empty places in the GaAs host lattice (interstitials) or replace As (antisites). Both these defects inhibit ferromagnetism of GaMnAs and worsen the material properties. The goal is then to eliminate these defects, in particular the interstitials, in the growth (and post-growth) process. A successful approach to meet this goal is described in the Dissertation.

The introduction gives the background to the structural properties of GaMnAs and the bare essentials of its physical characteristics and potential practical applications.

Chapter 2 is an overview of the growth and characterization methods, structural, and magnetic investigations. The samples used in the work were prepared by MBE. The epitaxy and the growth rate was checked by reflection high-energy electron diffraction (RHEED), the layer structure by the angular resolved x-ray photoelectron spectrum (XPS) methods. The temperature of the sample was determined by the band-gap thermometry, while the ferromagnetic moment was measured by SQUID. Simply learning the physical background of the above techniques as well as acquiring working knowledge here is an evidence of acquired scientific competence.

The next four chapters are devoted to original experimental results. Chapter 3 presents two important observations: the dramatic increase of the GaMnAs sample temperature during the MBE growth and the growth diagram indicating the transition curve for the roughening transition between the two and three dimensional growth modes. The temperature increase is explained by a simple model of radiation transfer between relevant heat sources in the MBE apparatus. A natural question I would have at this point is to ask about the growth of conventional highly p-doped GaAs. Taking, say, Zn or Be as acceptors, would the same behavior be expected? Actually, this question can be made more general: what is the electronic structure and properties of conventional-acceptor p-GaAs? What is special about the Mn impurities (except for magnetism) for the growth itself and for the electronic structure? Are there investigations of high-concentration Zn or Be doped GaAs? Another question is related to the growth itself: which measured characteristics of the samples attest to the homogeneous distribution of the holes (free carriers) in GaMnAs? Would one expect voids in the thinnest layers (of, say, 10-20 nm)? The growth diagram, in Fig. 3.14, is an important guidance to growers of GaMnAs. As discussed later in the thesis, the growth around the curve separating the two and three dimensional modes produces most optimum samples.

Magnetic properties of GaMnAs are investigated in chapter 4. The important results are the increase of the Curie temperature upon annealing the grown samples, as well as investigated magnetic anisotropies. Here also the explanation for the general observation of the optimum growth mentioned in chapter 3 is given by alluding to the behavior of antisites whose density decreases with increasing growth temperature. Also the rather bleak outlook for producing thick GaMnAs layers is given here. For the magnetic anisotropies, the experimental results were analyzed with respect to a phenomenological magnetoanistropy energetic model extracting the relevant cubic and in-plane uniaxial anisotropy constants. The dependence of the anisotropies on the post-growth procedure is demonstrated, as well as the temperature dependence is determined. I wonder: has a systematic investigation of the layer thickness dependence of the in-plane magnetic anisotropy been performed? Would one expect this anisotropy to be dependent on the thickness (keeping the Mn concentration fixed)?

The chapter 5, on transport properties, is rather concise, dwelling on the temperature dependence of the conductivity of as-grown and annealed samples. The measurements once again show the importance of annealing for making high quality GaMnAs. I would have expected a more elaborate discussion here. I understand that transport here is used only as a tool to characterize the quality of the layers, not as a topic itself. I would nevertheless have expected a much more detailed discussion touching on some important issues currently debated in the literature, to provide more appropriate context.

Finally, chapter 6 deals with annealing and the surface oxide etching. The main discovery here, important in the context of increasing the Curie temperature, is the role of etching in making high quality annealed GaMnAs. The description of the relevant physics here is rather straightforward, nicely illustrating the progress made by this discovery. The XPS analysis was performed to learn about the structure and composition of the surface oxide layer.

The Dissertation is written in a very clear and concise style; it is well organized, presenting, apart from the bulk of experimental results, relevant qualitative descriptions and working hypotheses. The work is placed in perspective of related activities of other groups. What I find missing, though, are a more elaborate introduction to the electronic structure of Ga(Mn)As, a comprehensive and authoritative outlook, prospects, and challenges, as well as ideas of using the line of the work to make materials compositions for practical heterostructures for spin injection, spin diodes, etc.

To summarize, Mr. Kamil Olejník has demonstrated a high level of scientific competence by mastering and helping to develop the technology and science of the epitaxial growth of high-quality GaMnAs; this work has made strong impact on the field. He has gained relevant research experience and experimental skills, as a prerequisite to the doctoral degree. He has also had extensive collaborations with many workers, as acknowledged in the Dissertation, on many stages of the experiment, which is also highly desirable for a young scientist. He is a co-author of numerous papers, of those several Physical Review Letters (as a first author he appears in several specialized journals and a Physical Review B). Mr. Olejník has demonstrated the ability to perform independent creative scientific work.

Based on the above evaluation I recommend accepting the presented Dissertation to the PhD defense.