NIRT: Formation and Properties of Spin-Polarized Quantum Structures in Magnetic Semiconductors by Controlled Variation of Magnetic Field on the Nanoscale

Program Objectives: The objectives of the research program supported by NSF/NIRT Grant DMR02-10519 are to achieve localization of spin-polarized states in magnetic semiconductors induced either by inhomogeneous magnetic fields generated by intentionally-patterned ferromagnetic overlays; or by magnetic vortices that arise naturally in superconducting films deposited on magnetic semiconductors. The program involves a close coupling of molecular beam epitaxy facility at Notre Dame (used to fabricate the magnetic semiconductor films required for the program, directed by J. K. Furdyna); lithography and ferromagnetic film deposition (carried out at the University of Illinois at Chicago by V. Metlushko and his group); theory of localization and of magnetic semiconductors generally (carried out under the direction of B. Janko); magnetic characterization (performed both at Notre Dame and at Argonne); fabrication of magnetically confined single and double quantum-dot devices (by Albert M. Chang at Duke);and spectroscopic, magneto-spectroscopic, and magneto-transport studies performed by Margaret Dobrowolska and her graduate students.

Progress to Date: During the first stage of the project our research has focused on the development of basic materials and multilayers which are suitable for the observation of magnetically-induced localization; on the understanding of the basic properties of magnetic semiconductors required for this purpose, including extensive theoretical studies focused on these goals; and on setting up of diagnostic laboratory equipment to be used in the study of the nanostructures produced by the magnetic field singularites. In addition to these basic steps required for achieving the goals of the program, we have also made preliminary attempts at actual lithographic fabrication of the proposed nanostructures. These specific findings and related progress are described below.

Fabrication of Materials: In the materials fabrication area we focused on two activities: development and optimization of ferromagnetic alloys suitable for the purposes of the NIRT program; and fabrication of hybrid nanostructures (including lithography) involving paramagnetic semiconductors and ferromagnetic metal films. The growth of ferromagnetic semiconductors involved introducing Mn into the III-V semiconductor host via low-temperature molecular beam epitaxy. During the past two years we focused on three aspects of this program. First, we worked on the optimization of a series of random ferromagnetic alloys, including GaMnAs, GaMnSb, InMnAs, and InMnSb. Second, we explored the formation of digital ferromagnetic alloys, by inserting monolayers of Mn into the III-V matrix. And finally, we explored the effects of annealing and modulation doping of III-Mn-V alloys on their ferromagnetic properties, with an eye at improving the value of the Curie temperature.

Magnetic Characterization: A great deal of effort has been devoted to the study of magnetic properties of these systems, including magnetic domain structure, both of which are expected to be of crucial importance at later stages of the NIRT program. These studies were carried out in collaboration with our colleagues at Argonne National Laboratory. The growth program and domain imaging were complemented by systematic studies of ferromagnetic resonance and spin waves. Our theoretical effort in this area has clearly revealed that in the III-Mn-V ferromagnetic alloy films the magnetic properties are graded along the growth direction. This knowledge is expected to be crucial in designing future nanostructures intended for achieving magnetically-induced localization.

Development of Diagnostic Tools: In diagnostic equipment required for the studies of magnetically-induced localization, major progress has been made in two areas. First, we have set up magneto-optical capabilities which will allow us to measure *magneto-Kerr effect* and *magnetic circular dichroism* – two of the most sensitive techniques for optically characterizing magnetic quantum structures. These new techniques, added to standard optical spectroscopy that was already in place, also allows us to study the properties of ferromagnetic films and multilayers, providing an invaluable tool for characterizing the films as such, before we invest time in fabricating nanostructures based upon them. We have also set up the capability for measuring *micro-photoluminescence*, which is the 'work-horse' technique for detecting quantum structures (such as individual quantum dots). This latter accomplishment has added significantly to our capabilities in optical diagnostics of the magnetically-induced localization effects constituting the ultimate goal of the program.

Lithographic Patterning: We have, finally, begun our first attempts at lithographic fabrication of ferromagnetic discs (permalloy) on ZnMnSe, and search for magnetically induced localization effects produced by the magnetic field singularities emanating from the nanoscale permalloy discs. These initial experiments have clearly indicated that one needs to employ *quantum well* structures to achieve such localization. Based on the feedback from our initial experiments we have designed the next generation of structures, which involve ZnCdMnSe quantum well layers between ZnSe barriers. And, in parallel with this effort, we are also developing growth conditions for analogous structures based on Te instead of Se, in order to increase the parameter space available to us in this investigation. We now envision a systematic series of experiments, with an eye on identifying the optimal parameters (barrier and well thicknesses, and materials compositions) for achieving optimal conditions for magnetically induced localization.

Education and Training: In addition to skills in spectroscopy and electrical transport needed to achieve the project goals, the graduate students and post-docs involved with this program get a very significant amount of exposure to materials fabrication and structural characterization. Thus individuals emerging from this program are automatically well-rounded in materials science generally. The PI and the Co-PIs feel that this is extremely important, particularly in the case of graduate students, to have a clear understanding of what it takes to fabricate hybrid semiconductor heterostructures and nanostructures, not only in terms of design, but in terms of cost and production time. This exposure prepares the students for the realities of technology when they complete their respective degrees. We feel that such education provides optimal preparation of the respective graduate students as they enter the world of technology after completing their Ph.D. research, thus contributing to U.S. manpower needs in materials science and nanotechnology.

Outreach and collaborations: Our primary outreach activity is to act as a resource for the U.S.geometries, and their nanostructures, as well as our understanding of these complex systems acquired in the course of this project – both theoretically and experimentally. As a measure of this, during the past 12 months we have interacted with *over twenty* other institutions by providing them with specimens, or by engaging in other collaborative ventures. One should note that among these collaborations are three *undergraduate colleges* (Goshen College, Goshen, IN; Kenyon College, Gambier, OH; and Rose-Hulman Institute of Technology, Terre Haute, IN), where both faculty and undergraduate students take part in measurements on our specimens, and collaborate with us on the interpretation of these measurements.

An important characteristic of our program is the *international* aspect of our activities. We are actively collaborating with Prof. Gerd Bacher at the University of Wurzburg, Wurzburg, Germany, on optical studies of single quantum dots; with Prof. Jacek Kossut of the Institute of Physics, Polish Academy of Sciences, Warsaw, Poland, on the theory of magneto-optical phenomena in magnetic semiconductors and semiconductor-ferromagnetic hybrid structures, and with Prof. George Mihaly from The Technical University Budapest on point-contact spectroscopy and magneto-transport measurements under pressure. There are several active international collaborations within the theory effort: we work together with Prof. Gergely Zarand of the Technical Univeristy, Budapest, on strong correlation phenomena and electronic properties of magnetic semiconductors, and with Prof. Mona Berciu on spin localization in hybrids. In addition to many continuing international collaborations, the PI of this project and his entire theory group have recently spent a semester at The Technical University of Budapest, giving lectures and planning collaborations with the Faculty there; one of the co-PIs (JKF) has spent a semester at Warsaw University; and the other Co-PI has spent three months at the Institute of Physics of the Polish Academy of Sciences, both engaged in similar activities. We have recently hosted three exchange graduate students from Poland, one from Brasil, and one from Hungary. Furthermore, Prof. Wojtowicz (a Senior Fulbright Scholar) and Dr. Sanghoon Lee (a frequent visitor from Korea) are closely involved with this project. Our group has thus developed a particularly active record of *two-way* international visits with the countries of Central and Eastern Europe and the Far East, which contributes to mutual international good will and understanding.

Broader Impact of the Program: The understanding of quantum dot formation induced by magnetic field singularities arising either from patterning of ferromagnetic overlays or from vortices naturally occurring in superconducting overlays achieved under this program will automatically contribute to the understanding of all other systems where localization of spin-polarized carriers plays a role. The spectroscopic and transport studies aimed at elucidating these issues are also likely to contribute to the fast-developing area of nanoscience, spin electronics, tunneling phenomena, and to technology in general. Finally, our contributions to the development of ferromagnetic semiconductors which we are carrying on as this program develops (such as the optimization of the properties of GaMnAs, GaMnSb, InMnAs, and InMnSb ferromagnetic alloys; quantitative determination of magnetic anisotropy and mapping out its spatial profile; and the identification of the role of Mn interstitials in determining the Curie temperature of these systems) also provide valuable input to the fast-developing field of spin-based electronics ('spintronics'), where it is hoped that the spin degree of freedom of electrons will ultimately lead to new spin-based devices.