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19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Growth and physical properties of diluted magnetic semiconductors (DMS) were investigated. Growth included Bridgman, solid state recrystallization, and liquid phase epitaxy of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Mn_xCd_yTe$. Very uniform crystals were produced by solid state recrystallization. Physical properties studied included magnetization, optical response, and magnetotransport. From magnetization the exchange interactions among magnetic ions have been deduced. Modulated spectroscopy gave details of the electronic structure of DMS and the quality of the material was indicated by the line widths. Magnetotransport, carried out in some cases to 30 T, showed a large negative magnetoresistance and subsequent increase. The $Hg_{1-x-y}Mn_xCd_yTe$ has considerable promise for avalanche photodiodes between 1.2 and 1.8 µm. micrometers

Mercury(1-x) Manganese(x) Telluride   mercury(1-x-y) Manganese(x) Cadmium(y) Telluride

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Final Report

Diluted Magnetic Semiconductors

Grant Number: DAAG29-85-K-0052

Author of Report: J.R. Anderson

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1. Forward

Diluted magnetic semiconducting (DMS) systems are compound semiconducting systems composed of cations from columns II or IV of the Periodic Table of the Elements and anions from column VI. The term magnetic refers to the fact that some of the cations are replaced by magnetic ions such as manganese, cobalt, iron, gadolinium, or europium. These systems provide an opportunity to investigate the confluence of semiconductor physics and magnetism in a single system. That is, the semiconducting properties are influenced strongly by a magnetic field and the semiconducting carriers contribute to the magnetic features. A summary of some of these properties has been given by Furdyna.[1]

In the present report we describe our investigations of the responses of DMS systems to magnetic fields, light, and electric fields.

2. Report

A. Statement of the Problem Studied

This report summarizes our investigations of methods of growth and of physical properties of DMS systems. The aim of our studies was to learn how the magnetic and semiconducting properties of DMS systems are related so that the potential of these materials for application can be realized. To accomplish this we investigated Bridgman, solid-state-recrystallization, and liquid-phase-epitaxy growth.

magnetization, magnetotransport, and modulated reflectance. Our studies suggest that magnetic-field modulation may be used to enhance the device capabilities of these materials.

B. Summary of Most Important Results

Our most important results are summarized as follows:

1. A recipe for Bridgman growth of $Hg_{1-x}Mn_xTe$ was developed; single crystals with mobilities comparable to those of $Hg_{1-x}Cd_xTe$ with the same energy gap have been obtained. Calibration curves making use of the ratios of the x-ray line intensities, $CdL\alpha/TeL\alpha$ and $MnK\alpha/TeL\alpha$, from electron microprobe energy dispersive analysis, have been obtained for determination of the x-values in both $Hg_{1-x}Cd_xTe$ and $Hg_{1-x}Mn_xTe$.[2]
2. Solid-state recrystallization growth of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x}Cd_xTe$ produced high-quality single crystal boules of length 7 cm in which the variation of x over the central 4 cm was less than 5%. Defect densities have been estimated from transport measurements. For example, for $Hg_{.875}Mn_{.125}Te$ the room temperature electron concentration was about $2x10^{16}cm^{-3}$, a value consistent with estimates of the intrinsic density at the room temperature band gap (230 meV). At low temperatures the samples became p-type and magnetic boiloff was observed.[3] Some crystals were converted to n-type by annealing in Hg vapor.
3. In collaboration with Dr. S.H. Shin of the Rockwell Science Center $Hg_{1-x-y}Mn_xCd_yTe$ crystals were grown by liquid phase epitaxy and the electronic structures studied by electrolyte electroreflectance and magnetotransport. This quaternary system has been developed as a promising candidate for avalanche photodiodes at wavelengths between 1.2 and 1.8 µm.[4,5] In particular, by appropriate choices of x and y, resonance structures have been obtained at 1.55 µm. This work has been summarized in our patent on avalanche photodiodes.[6]
4. A new technique, mobility spectrum analysis (MSA) employs a combination of the low-field Hall signal and magnetoresistance to obtain the carrier concentration as a continuous function of mobility. As a result, we are able, without

additional assumptions, to extract the maximum amount of information from the data concerning the types of carriers contributing to the conductance and their mobilities. This approach has been shown to work well for $Hg_{1-x}Cd_xTe$ and HgTe, materials for which the energy bands are not influenced significantly by a magnetic field.[7,8] Up to now, however, the MSA technique has not been successful for DMS systems because a magnetic field has a strong influence on the electronic structure, but work on this problem is continuing.

5. Magnetization studies of both II-VI and IV-VI DMS systems have shown that the dominant contributions to the magnetization are single magnetic ions and magnetic ion pairs. We have developed a model to obtain the exchange parameters for these DMS materials from a combination of high-field magnetization and low field susceptibility studies.[9,10,11,12]

6. Photoreflectance has the potential to be very important for characterization of semiconducting systems because no electrical contacts are needed and the technique is nondestructive. We have developed an extremely successful double modulation experimental technique for photoreflectance. In addition, following the work of Aspnes and Frova,[13] we have derived a model that takes account of the spatial variation of the internal electric field at surfaces and interfaces and fits both the exciton structure and the Franz-Keldysh oscillations. Consequently we believe photoreflectance now has a fundamental basis like electroreflectance and can be applied systematically as a semiconductor characterization tool.[14]

7. Anodization studies supplemented by surface Raman scattering are in progress. We have shown that the surface-enhanced Raman effect is a powerful tool for examining the reaction products produced during oxidation/reduction cycles at the surface of a DMS system such as $Hg_{1-x}Mn_xTe$.

C. Publications and Technical Reports

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D. Participating Scientific Personnel and Advanced Degrees Earned

R.G. Mani	Ph.D.
M.M. Gorska	
C.R. Lu	Ph.D.
D. Streett	
L. Ghenim	
T. McNair	
J.A. Nobel	Ph.D.
W.A. Beck	Ph.D.

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