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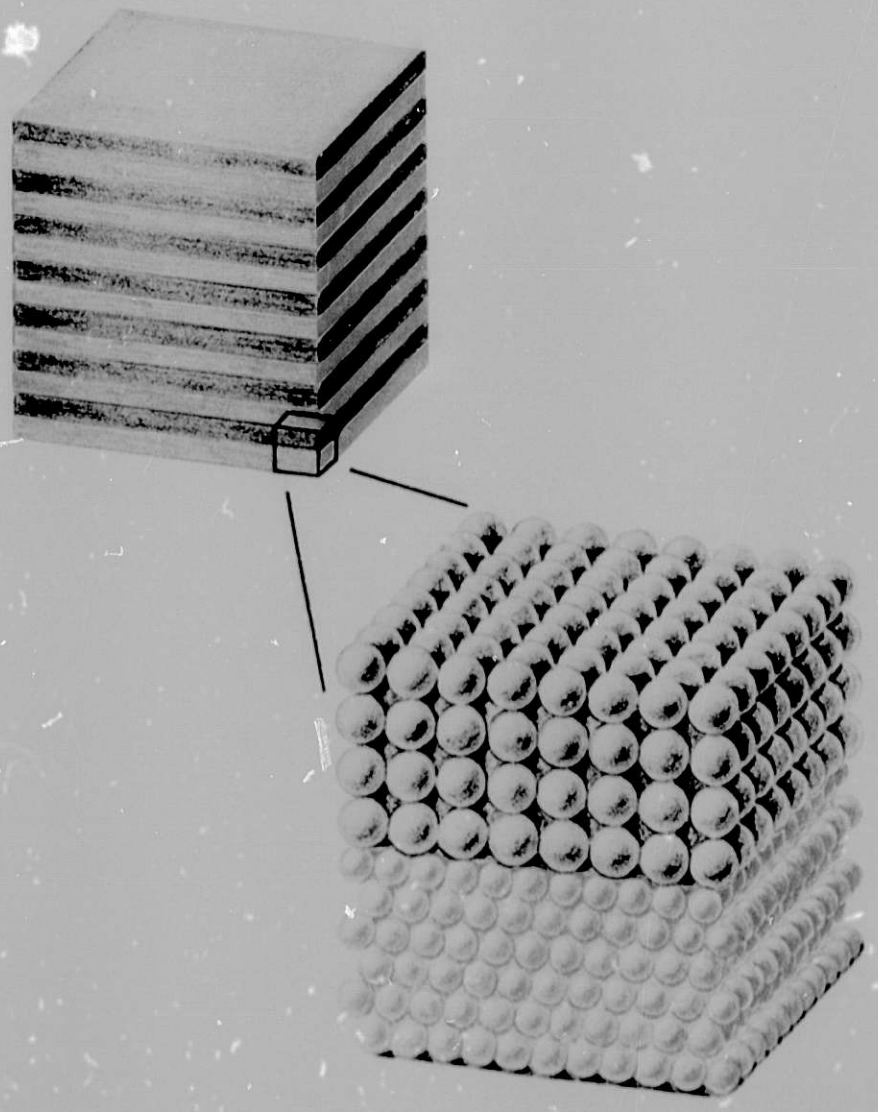
ABSTRACTS

INTERNATIONAL WORKSHOP ON

ARTIFICIAL SUPERLATTICES

OCTOBER 30-31, 1980



CHAMPAIGN-URBANA, ILLINOIS, USA

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THE OFFICE OF NAVAL RESEARCH

ARGONNE NATIONAL LABORATORY

PROGRAM AND ABSTRACTS

for the

WORKSHOP ON ARTIFICIAL SUPERLATTICES

October 30-31, 1980

AT

University of Illinois

Urbana - Champaign, Illinois, USA

sponsored by

OFFICE OF NAVAL RESEARCH

FOREWORD

The engineering of novel materials using sophisticated preparation techniques has received considerable attention in recent years. This interest has been mainly stimulated by recent developments in preparation techniques such as Molecular Beam Epitaxy, Thermal Vapor Deposition and Sputtering. These advances in deposition technology allow for the first time the preparation of layered materials with well defined layer thicknesses approaching interatomic spacing and opens up new avenues for the production and stabilization of materials that do not occur in nature. In addition to the extensive experimental work on artificial semiconductor superlattices there has been a parallel, almost independent, development relating to artificial metallic superlattices. Although the experimental sophistication of the field is considerable the development of major related theoretical ideas has not kept pace.

In view of the large body of experimental work, a pressing need exists for the development of conceptual ideas relating to the novel physics that is created by artificially adding a new periodicity to the lattice. Because of this the Office of Naval Research is sponsoring the first "Workshop on Artificial Superlattices", Oct. 30-31, 1980 at the University of Illinois, Urbana-Champaign. It is hoped that a small workshop, where theorists and experimentalists in metal and semiconductor physics are brought together, will be conducive to intimate interaction and development of new conceptual ideas.

The Program Committee has compiled a list of possible participants which were invited to contribute to this workshop. Since the field is in its inception, the participants were not all expected to have done earlier work in the field. Judging by the enthusiastic response it is hoped that the workshop will produce many fresh, yet unexplored, viewpoints and ideas. To allow a wider disemination of the results, a summary will be written by the organizers and published in the open literature.

L. R. Cooper R. G. Brandt
Office of Naval Research

WORKSHOP ORGANIZATION

PROGRAM COMMITTEE

Professor M. Beasley - Stanford University

Dr. L. Esaki - IBM

Professor P. Flynn - University of Illinois - Urbana-Champaign

Dr. A. Gossard - Bell Laboratories

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Preliminary list of Participants

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Dr. L. Cooper	-	Office of Naval Research
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Professor D. Dahlberg	-	University of Minnesota
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Professor P. Flynn	-	University of Illinois - Champaign-Urbana
Professor A. Freeman	-	Northwestern University
Professor T. Geballe	-	Stanford University
Professor A. Goldman	-	University of Minnesota
Dr. A. Gossard	-	Bell Laboratories
Dr. K. Gray	-	Argonne National Laboratory
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Professor J. Hilliard	-	Northwestern University
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Dr. D. J. Nagel	-	Naval Research Laboratory
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Professor L. Sham	-	University of California - San Diego
Dr. S. Sinha	-	Argonne National Laboratory
Professor D. L. Smith	-	Caltech
Dr. H. Stormer	-	Bell Laboratories

Preliminary list of Participants (cont.)

Dr. M. Strongin	-	Brookhaven National Laboratory
Dr. C. Weisbuch	-	Bell Laboratories
Dr. H. Weinstock	-	Office of Naval Research
Dr. R. M. White	-	XEROX-Palo Alto
Dr. S. Wolf	-	Naval Research Laboratory
Mr. J. Q. Zheng	-	Academia Sinica Beijing

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Keynote Address

SEMICONDUCTOR SUPERLATTICES

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Structure and Elastic Properties

COHERENCE AND STRUCTURE OF ARTIFICIAL SUPERLATTICES

by

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Abstract

X-ray scattering measurements have been made on semiconductor superlattices,[1,2] $(GaAs)_n(AlAs)_m$, with values of n:m ranging from 1:1 to 10:4 and on metallic superlattices,[3] Cu_nNi_m, with n:m from 3:3 to 30:30. The position, intensity and width of the fundamental Bragg reflections and the satellites associated with the chemical modulation have been studied, and they provide respectively 1) the modulation wavelength, 2) the amplitude and shape of the composition wave and of the associated strain wave, and 3) the coherence of both the chemical modulation and of the average lattice. In addition both systems show diffuse scattering which is associated with clustering at the interface.

1. P. D. Dernier, D. E. Moncton, D. B. McWhan, A. C. Gossard, and W. Wiegmann, Bull. Am. Phys. Soc. 22, 293 (1977).

2. R. M. Fleming, D. B. McWhan, A. C. Gossard, W. Wiegmann, and R. A. Logan, J. Appl. Phys. 51, 357 (1980).

3. E. M. Gyorgy, J. F. Dillon, Jr., D. B. McWhan, L. W. Rupp, Jr., L. R. Testardi, and P. J. Flanders, Phys. Rev. Lett. 45, 57 (1980).

Mechanical and Magnetic Properties of Composition Modulated Foils

by J. E. Hilliard and N. K. Flevaris

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During the last few years studies have been made of the mechanical properties of Au-Ni, Cu-Ni, Cu-Pd and Ag-Pd foils containing short wavelength (8-80 Å) composition modulations produced by vapor deposition. It was observed that these foils have a significant increase in elastic modulus (by a factor of two to four) over homogeneous foils or bulk single crystals of the same average compositions. These results will be discussed together with anomalous effects that have been observed in the magnetic properties of modulated foils.

ON THE ELECTRONIC STRUCTURE AND RESPONSE OF METALLIC ARTIFICIAL SUPERLATTICES

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In studying the elastic properties of coherent composition modulated (CCM) Ag-Pd (and isoelectronic) alloys Hilliard and co-workers[1,2] have found an elastic modulus Y_{111} to behave as

$$Y_{111}(c_o,\lambda,A)=Y_{111}(c_o)+S(\lambda)A^2$$

where $c_o=0.55\pm0.10$ is the mean Pd concentration and λ and A are the wavelength and amplitude of the alloy composition modulation. Most surprising is the behavior of the "slope" S, which is resonance-like versus λ for $15<\lambda<25$Å and vanishes outside this range. Hénein[2] interpreted this as due to the screening anomaly which arises when the charge density wave gap first opens at the Fermi surface (FS), and his model calculations reproduced the general experimental features.

Recent CPA calculations[3] of paramagnetic Cu-Ni alloys give a connected FS similar to that of Cu (down to Cu concentrations $\gtrsim$0.2) which is consistent with the interpretation of position annihilation data. Similar behavior in the Ag-Pd alloys, which is expected, would invalidate the Hénein interpretation which requires disconnected FSs. Other doubts arise, e.g. is it sufficient for large modulation amplitudes $A\gtrsim0.3$ atomic fraction to consider only the mean concentration band structure?

Here we contrast the electronic structure viewed from a more fundamental standpoint with the perturbed electron gas approach of Hénein. Rigorously, the large superlattice unit cell gives rise to lower symmetry, which folds down the Brillouin zone and introduces anisotropy, and allows long wavelength "local fields" which may affect screening processes. However, it will be pointed out that, particularly for the unique case of a CCM with a single Fourier component,[1,2] it may be disadvantageous to work within the rigorous Brillouin zone. An interpretation of the resonant S behavior in CCM alloys in terms of the existence (rather than absence) of FS necks along <111> will be presented.

1. W.M.C. Yang, T. Tsakalakos and J.E. Hilliard, J. Appl. Phys. 48, 876 (1977).
2. G. Hénein, Ph.D. Thesis, Northwestern University, 1979.
3. B. Bordon, W.M. Temmerman, B.L. Gyorffy and G.M. Stocks, Inst. Phys. Conf. Ser. 39, 402 (1978).

Neutron Diffraction Investigation of Layered Coherent Structures

(G. P. Felcher, Argonne National Laboratory and J. W. Cable, Oak Ridge National Laboratory

Neutron diffraction enables the study of the structural and the magnetic properties of coherently layered alloys. The coherence of the succession of the vapor-deposited layers of two components gives rise to a series of diffraction lines in the region of small scattering angles, when the lamina is set in reflection geometry. Each of these lines represents one of the harmonics in which is analyzed the modulation of physical properties between alternate layers: modulation in composition, density and ordered magnetic moment. If the lamina is epitaxially grown, these lines appear as well at the left and the right of each Bragg reflection.

For the structural part, neutron diffraction is complementary to X-rays for laminae for which in the latter technique there is poor contrast between the two layers. A case in hand, and which we have studied, is a lamina of cobalt-nickel. The greater penetration of the neutrons demands a careful choice of the substrate in order to obtain a successful pattern from micron-thick samples.

More unique of neutron diffraction is the determination of the magnetic structure. Using polarized neutrons, we studied films of layered copper-nickel and found that nickel has an average moment of 0.3 μ_B, and that all the nickel moments are practically the same. In view of the drastic dependence of the local moment of nickel on its chemical and magnetic environment in desordered nickel-copper alloys, the last finding brought us to conclude that in the layered material clustering occurs in each plane. This result illustrates the power of the technique, by which we are planning to study the microscopic magnetic response of novel materials, such as layered palladium-gold.

R.-P. Haelbich

HASYLAB at DESY
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Multilayer Coatings for Soft X-Ray Mirrors

Multilayer coatings consisting of amorphous films of heavy metal alloys and light elements like Carbon or Boron are used as near normal incidence reflectors in the 100 - 200 Å wavelength region. Film thickness control during deposition by a soft X-ray reflectometer makes it possible to produce coatings with a large number of layers all contributing in phase to the reflected wave. Reflectivity values above 10% are obtained at near normal incidence. Close to grazing incidence (grazing angles between 1^{o} and 2^{o}) the maximum reflectivities are above 50% for λ = 1.54 Å. The films form very smooth boundaries and the ratio of specular reflected to diffusely scattered light is the same as for a single thick film with a root mean square surface roughness of σ = 3 Å.

The Geometric and Electronic Structure of fcc Metal Overlayers on the Nb(110) Face

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and

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We have studied the structure of Pd,[1] Cu and Ni layers on the Nb(110) surface. For thicknesses of less than one monolayer these materials form a commensurate 1x1 overlayer on the Nb(110) surface. For Pd layers a transition from the commensurate phase to the (111) face of fcc Pd takes place at a thickness of about one monolayer. In the case of Cu on Nb the situation is somewhat more complicated and we believe a transition to the (111) fcc Cu structure takes place at about two layers. In the case of Ni on Nb the results are more preliminary but both the commensurate structure and the (111) face of fcc Ni are evident.

Besides the above LEED studies of these structures, photoemission measurements have also been done to determine the electronic structure. In the case of Pd we find that when it is in the commensurate structure there is a low-lying filled d-band (~2 eV below E_F) and low d-band density of states near E_F.[2] When the transformation to the (111) face occurs there is a rise in the d-states near E_F and the usual Pd band structure is finally reproduced. The chemical reactivity of the two Pd[1,2] surfaces is completely different; H_2 readily dissociates on the (111) surface, but not on the 1x1 commensurate structure and we associate this difference with the different d-band densities near E_F. In the case of Cu there are filled d-bands below E_F in both structures but the detailed photoemission structure changes in the two phases. In the case of Ni very preliminary results show a filled d-band in the commensurate structure which would indicate the absence of ferromagnetism.

We hope to have some results on the electronic structure of superlattices of near monolayer metals formed by adding an additional Nb layer over the fcc metal already deposited and characterized on the underlying (110) Nb. Recent work on thicker layers indicates that this scheme should work.[3]

[1]Myron Strongin, M. El-Batanouny and M. A. Pick. To be published in Phys. Rev.

[2]M. El-Batanouny, Myron Strongin, G. Williams, R. J. Smith and J. Colbert. Submitted to Phys. Rev. Letters.

[3]Ivan K. Schuller, Phys. Rev. Letters 44, 1597 (1980).

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*Supported by the US DOE under contract DE-AC02-76CH00016.

Transport and Electronic Properties

ELECTRONIC SPECTRA OF SUPERLATTICES †

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ABSTRACT

One of the properties of superlattices that may make them uniquely suited for a number of applications is their potentially, unique electronic spectra. For example, for superlattices made up of thin layers of semiconductors electronic states and impurity binding energies may be substantially different from that in the bulk and adjustable by changing the parameters of the superlattice. To illustrate this point we will present theoretical results on HgTe/CdTe superlattices where the direct band gap can be adjusted for fixed alloy composition. For this superlattice the theoretical value of the band offsets are such that one might expect useful values of the transport coefficients for electrons and holes moving normal to the layers. Further, we show that the binding energy of a Coulombic center in a superlattice can be adjusted by changing the layer thickness. For donors in the GaAs layers in GaAs/AlAs superlattice, we show that the binding can be increased from approximately 5 meV to 20 meV by narrowing the GaAs layer thickness.

† Work supported in part by the Army Research Office under Contract No. DAAG29-80-C-0103

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ELECTRONIC SPECTRA OF SUPERLATTICES

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SURVEY OF EXPERIMENTAL TECHNIQUES APPLICABLE TO ELECTRONIC STRUCTURE MEASUREMENTS IN ARTIFICAIAL SUPERLATTICES

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Energy bands, densities of states and charge distributions are fundamental to the properties of solids. A wide range of techniques is available for theoretical computation and experimental measurement. Here we assess the potential utility of spectroscopic methods for study of bonding in multilayer materials.

Electron spectroscopy[1] has proven to be extremely valuable for surface and near-surface electronic structure studies because of the short range of photo-stimulated electrons. Electrons with energies near 100 eV have mean free paths near 5A. Hence ultraviolet photoemission spectroscopy may have limited utility for study of bonding and charge transfer inside artificial superlattices. X-ray induced photoelectrons can escape from more than one layer of a sample with layer thickness of 50A or less. Hence higher-energy photoelectron spectroscopy should yield useful information on mulitlayers.

Several x-ray methods[2] yield electronic structure information: line and valence band emission spectroscopy, absorption spectroscopy, Raman and Compton scattering spectroscopy, isochromat spectroscopy and appearance potential spectroscopy. Of these, emission spectroscopy will yield valuable information on multilayers because of the relatively long escape depth of x-rays. Absorption spectroscopy (EXAFS) should produce atomic as well as electronic structure information.

A summary of the strengths and weaknesses of electron and x-ray spectroscopy methods as applied to artificial superlattices will be presented.

1. V.V. Nemoshkalenko and V.G. Aleshin, Plenum Press, New York (1979).

2. D.J. Nagel and W.L. Baun in L.V. Azároff X-Ray Spectroscopy, McGraw-Hill (1974) pp. 445-532.

SEMICONDUCTOR SUPERLATTICE STRUCTURES BY MOLECULAR BEAM EPITAXY

by

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ABSTRACT

Superlattices of GaAs and AlAs have been grown by molecular beam epitaxy for structural, optical, electrical, and phonon studies. Structural measurements showing layer smoothness at the atomic monolayer dimension and layer thickness control at the several per cent level in these superlattices are corroborated by optical absorption, phonon excitation, and magnetoresistance measurements. The modulation doping technique for producing high carrier mobilities by separation of impurities and charge carriers will be reviewed. Transport perpendicular to the superlattices permits barrier height measurement and production of nonlinear I-V characteristics and rectification. Optical pumping of superlattices has produced large conduction band spin polarizations and is a promising technique for production of free space beams of spin-polarized electrons. Superlattice phonon modes have been detected and resonant phonon interference filters produced from multilayer films.

Measurements of Current-Voltage Characteristics in GaAs-$Al_xGa_{1-x}As$ Layered Heterostructures

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ABSTRACT

Real-space electron transfer has been proposed as a mechanism for obtaining negative differential resistance in layered GaAs-$Al_xGa_{1-x}As$ heterostructures. It is based on thermionic emission of hot electrons from a high-mobility GaAs region to an adjacent low-mobility $Al_xGa_{1-x}As$ region when a high electric field is applied parallel to the heterojunction interface.

Monte Carlo computer simulations of electron transport in these GaAs-$Al_xGa_{1-x}As$ heterostructures indicate that for a high density of scattering centers in the $Al_xGa_{1-x}As$ layer a unique physical mechanism for negative differential resistance is achieved which is analogous in many respects to the Gunn effect. For doping densities of 10^{17} cm^{-3} in the $Al_xGa_{1-x}As$ the computer simulations predict current saturation only. We performed experiments in this range of doping and our experimental results are consistent with the theory in that a current saturation and no Gunn effect are observed. Depending on sample geometry we also observed unusual kinks and negative differential resistances (no Gunn oscillations) in the current-voltage characteristics at electric fields where real-space transfer should occur.

ANISOTROPY OF ELECTRONIC TRANSPORT IN MODULATION-DOPED GaAs-(AlGa)As SUPERLATTICES

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ABSTRACT

Separation of electrons from their ionized impurity in GaAs-(AlGa)As superlattices has been achieved via a new doping technique called modulation-doping (MD). This led to considerable improvement of the carrier scattering times; in particular in the low temperature range. However, so far measurements on this material are limited to transport in the plane of the layers. It is unclear if the MD-advantage remains for carrier transport perpendicular to the plane where a variety of interesting phenomena are expected. We present data on the angular dependence of the Shubnikov-deHaas effect of MD-superlattices from which we can deduce the angular dependence of the scattering time.

THEORY OF RANDOM SUPERLATTICES

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It is possible to grow semiconductor "superlattices" of, say, GaAs/$Al_xGa_{1-x}As$ with random distributions of thicknesses and alloy compositions. The resulting materials have randomly varying band edges, and are ideal for testing ideas concerning Anderson localization and diagonal- versus off-diagonal disorder.

We shall present a series of calculations of the densities of states of various simple models of such systems, and we shall illustrate how these models are related to the Anderson model and various theories of disorder in one dimension.

Research supported by the Office of Naval Research (NR00014-17-C-153).

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Transport Properties of Artificially Layered Metals.[+]

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We have studied the electrical resistivity and superconducting transition temperature of compositionally modulated alloys with special emphasis on NbTi. The room temperature NbTi resistivity displays the following three features: 1) At very short wavelengths (less than 20 Å) the resisistivity saturates a value of 113 $\mu\Omega$ cm; this valus is suprisingly close to the maximum 2D metaliic resistance (150 $\mu\Omega$ cm), 2) for wavelenghts between 20 Å and 142 Å the resistivity scale as the reciprocal of the wavelength, as would be expected for a wavelength limited mean free path. It is interesting that the extrapolation to infinite wavelength yields the bulk alloy value, 3) for wavelengths larger than 142 Å, this linear relationship breaks down and a limiting value of the resistivity of the resistivity given by the parallel resistivity of as deposited bulk films of Nb and Ti is approached. The superconducting transition temperatures as determined from the magnetic susceptibility ranges from 4.89°K at 14.3 Å to 3.40°K at 142 Å, the shortest and longest wavelength samples studies respectively. Data on the temperature dependence of the resistivity in NbTi will also be reported as well the effect of annealing

on the above phenomena. In addition transport, superconductivity, and magnetic data on some new CMA systems now under study will be reported.

+Work was supported by the NSF under grant No. DMR-78-24339, the NSF MRL under grant DMR-76-80847, the U.S. D.O.E., and the ONR under grant No. N00014-80-F-0024.

Magnetism and Superconductivity

STATIC MAGNETIZATION OF ARTIFICIALLY LAYERED CuNi FILMS*

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and

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ABSTRACT

Recently we have completed measurements of the static magnetization of a series of Compositionally Modulated Structures (CMS) made of the ferromagnetic alloy CuNi. We find that the saturation magnetization and the coercivity scale with composition modulation amplitude A and that the maximum magnetization per Ni atom is smaller than that of pure Ni. We can summarize the experimental data as follows: We find magnetizations reduced from that of pure Ni, in agreement with both neutron scattering experiments and band structure calculations. The saturation magnetization scales with composition amplitude, independant of modulation wavelength. The Curie temperature is amplitude independant and decreases with decreasing wavelength. We infer from the dependence of the magnetization on magnetic field that there is only a small magnetostrictive term, thus indicating the absence of large strains in this material. The temperature dependence of the saturation magnetization is in agreement with ferromagnetic resonance (fmr) measurements; with a Curie temperature that is independant of composition modulation amplitude.

*Work supported by ONR grant # N00014-80-F-0074 and by NSF grant #DMR 78-24339 and the NSF MRL Program under grant #DMR 76-80847.

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Magnetic Resonance in Magnetically Inhomogeneous Films

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The Kittel resonance formula, $\omega/\gamma = \sqrt{BH}$, is generalized to a magnetic film with an inhomogeneous magnetization, M(y). It is shown that for both normal and in-plane polarizations, a film in which the exchange coupling extends throughout the whole depth resonates at the same frequency as a uniform film with a magnetization $\langle M^2 \rangle / \langle M \rangle$ where $\langle \cdots \rangle$ denotes a spatial average.

Electronic Structure and Magnetism of Coherent Modulated Structures*

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Abstract

Considerable interest has recently been focused on the physics of artificially made short wavelength composition modulated structures. Particularly stimulating has been the report [1] of an enhanced magnetization of a short wavelength (30 Å) CuNi thin composition modulated film compared to that of pure Ni as deduced from ferromagnetic resonance experiments. Here we present a theoretical study of the electronic structure of coherent modulated structures (CMS) of CuNi in different geometries. Our initial studies [2] of 3+3 layers of a CuNi CMS modulated along the [111] direction, but including the local distortion due to the mismatch of the Cu and Ni lattice constants, have now been augmented with a similar study of a 6+6 layer CuNi CMS. In addition, we have studied the magnetic properties of CuNi (without local distortion) modulated along the [100] direction. The local magnetization on different Ni sites is compared with that of fcc Ni and tetragonally distorted Ni as in the modulated environment.

The calculations are performed for all electrons and all atoms in the (giant) unit cell using the Linear Muffin Tin Orbital method (LMTO) including fully relativistic (non-frozen) core states, semi-relativistic (no spin-orbit) valence states and the local spin density formalism to treat exchange and correlation to the potential for these magnetic systems.

We find no evidence for a complex magnetization distribution as proposed by White and Herring [3] to interpret the ferromagnetic resonance experiments. Instead, the spin magnetization of the Ni layers was found to be reduced relative to that of pure Ni: the central Ni layer moment is $0.50\mu_B$ whereas that of the interface Ni layers is $0.37\mu_B$. The large reduction of the 'interface' Ni layer moments is consistent with the magnetically 'dead' layers reported earlier for Ni layers deposited on a Cu substrate [4]. The calculated core polarization hyperfine fields, H_n, at the Ni sites also show a reduction proportional to that found for the spin magnetization. The small transferred Cu magnetic moments ($\sim 0.01\mu_B$) were found to result in large H_n values which are substantially larger than any Knight shifts observed for Cu. The results for the magnetic moments have now been confirmed by recent static magnetization measurements [5] and neutron scattering experiments [6] on CuNi composition modulated alloys.

Our most recent investigation are on 8 layer [100] Ni-Cu CMS with 1:7, 2:6, 3:5, 4:4 layers Ni:Cu to determine the effect of composition and to study the possibility of magnetically 'dead' layers reported by Bergmann. As in, the calculated moments are significantly reduced (to $0.14\mu_B$ for the 1:7 CMS) but not fully 'dead' and range to $0.5\mu_B$ for the 4:4 CMS.

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Superconductivity in Intercalated Layer Crystals

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Superlattices prepared by intercalating organic compounds into chalcogenide layer crystals exhibit unusual superconducting properties characterized by high critical fields, extreme critical field anisotropy and enhanced T_c's. The organic intercalation changes the layer spacing and modifies the charge density wave structure that exists in the pure crystal. Quenching of the charge density wave, modification of the electron-phonon interaction and charge transfer to the metallic layers from the organic molecule can all play a role in the enhanced superconductivity.

2H-TaS_2 and 4Hb-TaS_2 have been studied using a range of organic intercalates such as methylamine, dimenthylamine, pyridine and ethylamine. These produce T_c's in the range 3 - 7K and exhibit a wide range of critical field behavior. A Josephson coupling model has been developed to describe the superconducting behavior[1] and for the weakly coupled cases where the coherence length perpendicular to the layers becomes less than the layer spacing a dimension crossover occurs with upward curvature in $H_{c2\perp}$ and critical fields >200 kG. These substantially exceed the Pauli limit. Fits of the experimental data to the theory give values of the parameters which are consistent with dimensional crossover in 2H-TaS_2 intercalated with a number of different organics.

Data on 4Hb-TaS_2 intercalated with organics indicates a more complex behavior with a two part field induced resistive transition. The pure material consists of alternating metallic and semi-metallic layers which complicate the unit cell and band structure with two separate charge density waves existing. The angular dependence of the critical field anisotropy shows a strong departure from the effective mass model and at low temperatures the onset of some type of metal-insulator phase transition is observed (possibly connected with the development of an anisotropic current flow) before the crystal goes superconducting.

The superconductivity in these materials shows a strong interplay between the charge density wave, the organic layer, the dimensionality of the material, and the electron-phonon coupling. A variety of behaviors are observed and more detail of the band structure needs to be calculated before a complete analysis can be made.

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Vortex lattice melting in layered Superconductors*

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We consider a stack of superconducting films separated by insulating spacers in the presence of an external magnetic field normal to the film planes. The coupling between diamagnetic currents comprising the Abrikosov vortex lattice in each sheet results from a combination of Josephson tunnelling and magnetic interaction energies. At finite temperatures, disorder is induced in the lattice structure by the formation of dislocation pairs which are only weakly coupled between sheets for pair separations small compared to a critical distance r_c dependent on the strength of the Josephson coupling. As the temperature is increased towards the two-dimensional vortex lattice melting temperature[1] the dislocation pair separation is inhibited for spacings > T_c by the formation of strings (discommensuration lines) joining the dislocations. The melting of the vortex lattice is then expected to take place by a first order transition. Experimental results on critical fields of Nb-Ge composites by Beasley et al.[2] will be discussed in terms of these predictions.

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SUPERLATTICE QUASIPARTICLE STATES IN ORDERED INHOMOGENEOUS SUPERCONDUCTORS

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If the order parameter in a superconductor is spatially periodic with period a much greater than the coherence length ξ and if there are satisfied conditions required for the quasiparticles to sense this periodicity, then it has been predicted theoretically that the quasiparticle energies are redistributed. We shall term the new quasiparticle energy distribution, superconductor quasiparticle superlattice (SQS) states. In contrast to the BCS case, allowed levels (bound states) appear at energies E below energy Δ, and forbidden and allowed bands (scattering states) replace the continuum of allowed states above.

Demonstration of the existence of SQS states requires, in practice, detection of the scattering states, i.e., the allowed bands for $E > \Delta$, rather than the bound states. The latter do not differ qualitatively from those for a single, isolated well, and have been amply demonstrated in numerous tunneling experiments, and the subset of tunneling phenomena known as Tomasch oscillations. But it is the scattering states which are required in order to demonstrate the existence of SQS states in a superconductor: for $E > \Delta$, rather than the continuum of excited states found in the homogeneous superconductor or the single well, the quasiparticle energies are redistributed in allowed and forbidden bands, given a spatially periodic order parameter, $\Delta(x) = \Delta(x + a)$, and the satisfying of essential subsidiary conditions. While these conditions are similar in some respects to those for semiconductor superlattices, they contrast markedly in others, owing primarily to long range coherence and the vastly different spatial and energy scales.

We have found experimental evidence consistent with the existence of SQS states in a bulk superconductor. While those results refer to the intermediate state, near T_c, in bulk superconductors, they provide insights into possible extension to "permanent" order parameter superlattices satisfying conditions for SQS states in thin film configurations.

The conditions necessary for existence of SQS states in ordered, inhomogeneous thin films will be identified, practical thin film configurations proposed, and possible utility of such films in fundamental studies and applications discussed.

Phonons

SUPERLATTICE PHONON FILTERS AND PHONON OPTICS

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Selective narrow band transmission of high frequency phonons have been achieved[1] in superlattices of GaAs and $Ga_xAl_{1-x}As$. Superlattice structures, having periodically varying acoustical impedance, selectively reflect phonons having a wavelength of twice the superlattice period and are analogous to optical multilayer dielectic mirrors. The superlattice stacks are grown by molecular beam epitaxy and typically have about 100 layers. Superlattices with 100 Å period have a filter reflection resonance at a lattice frequency around 300 GHz, measured using monochromatic phonon techniques. These results have importance for a variety of phonon transport problems such as Kapitza conductance and anharmonic decay at boundaries and for electron transport and recombination processes involving phonon coupling in semiconductors. Possible uses of superlattice structures for the manipulation of phonon diagnostic beams in semiconductors[2] will be discussed.

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PHONON AND DISORDER EFFECTS IN QUANTUM-WELL-HETEROSTRUCTURE LASERS

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Phonon participation in the operation of certain forms of quantum-well heterostructure (QWH) lasers is a major effect and has a basis to be stimulated,[1] or even to be observed several phonons ($m\hbar\omega_{LO}$, m=1-6) below the lowest confined-particle transitions. To determine further what role phonons might play in QWH laser operation, we have conducted a series of experiments (4.2-300 K, pulsed and CW) on MO-CVD $Al_xGa_{1-x}As$-GaAs heterostructures in which large quantum wells, or bulk active layers ($L_z \geq 500$ Å), are coupled to phonon-generating arrays of coupled smaller wells ($L_z \sim 50$ Å) so that the behavior of bulk and quantum-well layers can be compared. For convenience, these heterostructures (undoped) are excited by photopumping, which is equivalent to the "hot-carrier" (phonon-generating) injection of an ordinary double heterojunction. Phonon-sideband laser operation below the confined-particle transitions of larger (GaAs) quantum wells, even bulk layers, can be induced by the large number of phonons generated in the smaller GaAs wells. This effect can be destroyed by disordering the smaller coupled wells and

any tendency of the smaller wells to form a phonon cavity. Induced phonon-sideband operation of an as-grown QWH has been used to make a unique measurement of the energy difference between the first-state light- and heavy-hole energies of a 200 Å quantum well (4.9 meV) and to measure directly the GaAs quantum-well LO-phonon energy $\hbar\omega_{LO} \simeq 41.0-4.9 = 36.1$ meV.

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PHONON FOLDING AND ANISOTROPY IN GaAs-AlAs SUPERLATTICES

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The properties of the phonons in GaAs-$Ga_{1-x}Al_xAs$ superlattices have recently received much attention. The phonon spectrum of these materials shows two interesting features which are dependent on the layer thicknesses. First, the new periodicity along the direction perpendicular to the layers results in a smaller, folded Brillouin zone (BZ) and the appearance of gaps in the phonon dispersion for wavevectors satisfying the Bragg condition. Second, the layering gives rise to anisotropic effects which may be absent in the constituent materials, as is the case for superlattices made out of $Ga_{1-x}Al_xAs$.

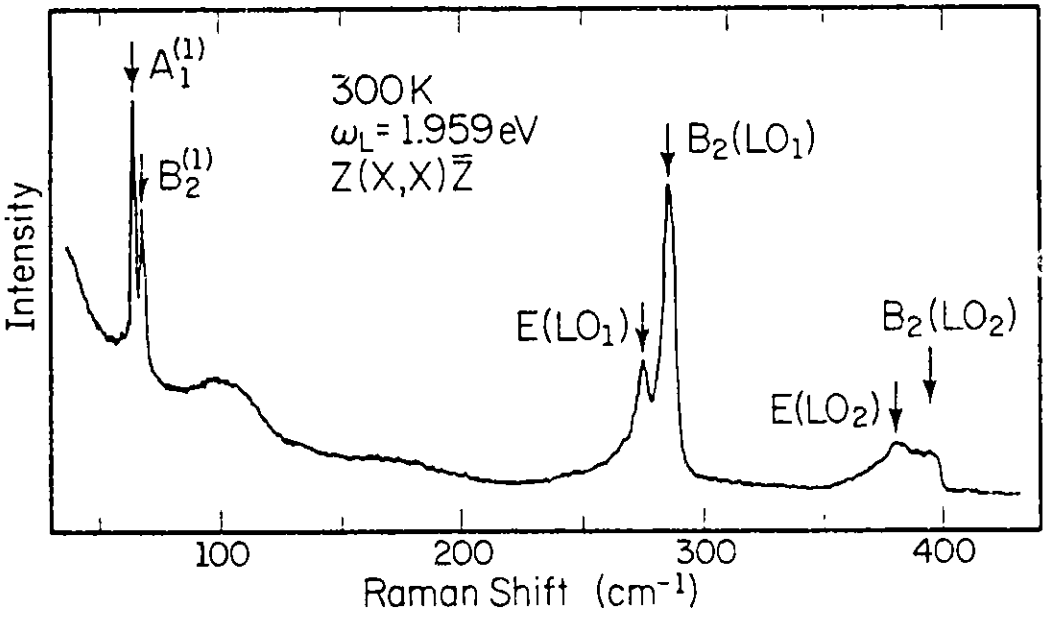

Figure 1. Raman spectrum of the 14 Å GaAs - 11 Å AlAs superlattice

Both effects, phonon folding and anisotropy, appear in the Raman spectrum shown in Fig. (1), of a superlattice made of alternating layers of 14 Å GaAs and 11 Å AlAs. This sample was grown by molecular beam epitaxy (MBE) on a GaAs substrate oriented such that the layers are perpendicular to the z = [001] direction. Only longitudinal modes are allowed for a Raman backscattering experiment from a {001} face. The two narrow lines at 63.1 and 66.9 cm^{-1} correspond to the scattering from longitudinal acoustic (LA) phonons folded to the zone center from q = $2\pi/d$ in the extended zone, where d is the superlattice period. The peaks at 277 and 286 cm^{-1} derive from the longitudinal optic (LO) phonon of bulk GaAs. The layering gives rise to the splitting of this phonon, which becomes an E - or a B_2 - symmetry mode when q propagates parallel or perpendicular to the layers. The LO - phonon of AlAs splits giving the $E(LO_2)$ and $B_2(LO_2)$ modes which appear in the spectrum of Fig. (1) at 382 and 399 cm^{-1}.

"LIGHT SCATTERING BY CARRIERS IN MODULATION-DOPED GaAs(AlGa)As SUPERLATTICES", A. Pinczuk and J. M. Worlock, Bell Telephone Laboratories, Holmdel, New Jersey, H. L. Störmer, R. Dingle, A. C. Gossard and W. Wiegmann, Bell Telephone Laboratories, Murray Hill, New Jersey

In modulation doped GaAs(AlGa)As heterojunction superlattices, electrons from Si donors in the (AlGa)As can be transferred to and confined in the GaAs layers. These electrons occupy states in a set of two dimensional subbands. The carriers in subband states of the superlattices constitute a high mobility multilayer two dimensional electron gas.

We have used the method of resonant inelastic light scattering to study the excitations of carriers in the modulation doped superlattices. With light scattering spectra we have been able to show that the electrons are indeed confined in the GaAs layers; and, more important, we observed excitations associated with the intersubband transitions of these carriers.

We found that odd as well as even parity intersubband transitions are active in light scattering. Furthermore, making use of polarization selection rules we were able to obtain separate spectra assigned to single particle and collective excitations. This is a unique feature of light scattering which allows the study of the bound states of the superlattice potential as well as the electron-electron interactions in these two dimensional electron systems.

The spectra of single particle excitations were used to obtain the subband spacings in superlattice samples having a range of layer thicknesses ($\sim$450Å-$\sim$200Å) and carrier concentrations ($\sim 3\times10^{11}$ cm^{-2} - 3×10^{12} cm^{-2}). The results are in good agreement with calculations of the subband structure which take into account the potential discontinuity at the interfaces and the band bending in the GaAs layers.

The spectra of collective intersubband excitations show the effects of depolarization electric fields and coupling to LO phonons. In conjunction with the single particle spectra, they were used to make the first direct determination of the matrix element of the Coulomb interaction associated with intersubband excitations of a two dimensional electron gas.

The results reported here demonstrate that resonant inelastic light scattering is a powerful tool to characterize charge carriers in semiconductor superlattices. In addition to subband spectroscopy, the method can also be used to study plasma properties and momentum distributions of carriers, in both single layer and superlattice semiconductor heterostructures.

Novel Periodic Doping Structures in GaAs Grown by MBE

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A new type of superlattice in GaAs consisting of a periodic sequence of thin p- and n-doped GaAs layers (also called "nipi" crystal) has been achieved by molecular beam epitaxy (MBE). The individual p-and n-type GaAs layers composing the structure are doped with Be$_{\wedge}^{as}$acceptor and Si as donor impurities, respectively. The varying space charge field of the ionized impurities in the direction of growth produces a periodic modulation of the energy bands in these nipi crystals. Therefore, we can expect a reduction of the effective band gap compared to pure GaAs. The existence of this novel superlattice effect in the periodic p/n multilayer structures in GaAs has been established by studying the optical absorption tails which extend far into the gap of the unmodulated semiconductor ($\hbar\omega < E_g^{GaAs}$) depending on the constituent doping levels and on the artificially introduced periodicity ($300 < d < 3000$ Å) of the crystal. A smaller band gap means a longer wavelength of absorbed or emitted light which is of great importance for application of the nipi crystals in optical devices.

In addition, the nipi crystals are extremely anisotropic with respect to their transport properties, and the electrons and holes are spatially separated from one another by the space charge fields, which prevents direct electron hole recombination. As a consequence, the charge carrier concentration and hence the current within the individual layers may be varied within wide limits by external bias or by absorption of light. This effect will be demonstrated on a model structure which may be cut out of a more extended nipi structure in GaAs. The current due to carriers of one type, I_{nn} or I_{pp}, can thus be modulated without losses by variation of the bias U_{np}. This behaviour resembles to some extent the familiar MOSFET. In our case, however, the whole nipi bulk is involved and high power modulation of the device can be expected.