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13. ABSTRACT *(Maximum 200 words)*

This is the final report of the project "Short-period Superlattice Materials for Heterojunction Bipolar Transistors", for the period 5/01/89 - 12/31/92. The goal of this project was to investigate the usefulness of short-period superlattices (SPSL) of InAs/GaAs and InAs/AlAs for heterojunction bipolar transistors (HBTs). Because of difficulties encountered early in the project in growing high structural quality SPSLs, the emphasis of the project was shifted to attempting to understand the growth of HBT material at low temperatures using migration-enhanced epitaxy and the incorporation of that material into HBTs. To summarize our technical results, we have grown InAs/GaAs SPSL on InP and GaAs and determined their surface roughening behavior with thickness and InAs content; correlated x-ray line widths with RHEED observations of roughening; developed methods to use migration-enhanced epitaxy to grow doped GaAs on (111) and (100) substrates, with material on both orientations having good mobilities; studied the properties of low-temperature conducting GaAs, determining Schottky barrier heights; and applied the migration-enhanced epitaxy technique to the low temperature growth of Be-doped base materials for HBTs with usable gain and no Be diffusion during growth.

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"SHORT-PERIOD SUPERLATTICE MATERIALS FOR HETEROJUNCTION BIPOLAR TRANSISTORS"

FINAL REPORT

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"SHORT-PERIOD SUPERLATTICE MATERIALS FOR HETEROJUNCTION BIPOLAR TRANSISTORS"

FINAL REPORT

Statement of the Problem Studied

The goal of this project was to investigate the usefulness of short-period superlattices (SPSL) of InAs/GaAs and InAs/AlAs for heterojunction bipolar transistors (HBTs). This was to be done by studying the growth and determining the structural and electrical properties of SPSL, then incorporating them in InGaAs/InAlAs HBTs. Because of difficulties encountered early in the project in growing high structural quality SPSLs, the emphasis of the project was shifted to attempting to understand the growth of HBT material at low temperatures and the incorporation of that material into HBTs.

Summary of Results

The stated goal of this project was to investigate the use of short-period superlattices in heterojunction bipolar transistors (HBTs). It was begun by growing $(InAs)_m(GaAs)_m$ SPSLs on InP, where m is a small integer representing the number of monolayers of a material in the superlattice period. The beginning concentrated on a study the growth process through RHEED observations. It became clear that the interface between InAs and Gas became rough on an atomic scale at very small thicknesses of the superlattice, even for m = 1. This led to a rapid degradation of RHEED pattern quality after only a few periods of the superlattice. The RHEED pattern was observed to worsen following the growth of the InAs layers, which are under compressive stress, and to recover somewhat following the growth of the GaAs layers, which are under tensile stress.

The focus then shifted to the growth of InAs/GaAs SPSLs on GaAs substrates. Since GaAs tended to smooth the surface, while InAs roughened it, it was reasoned that material containing more GaAs would retain a smooth surface and coherent superlattice growth to greater thicknesses than would the materials lattice matched to InP, with its equal amounts of InAs and GaAs. The average lattice mismatch of a SPSL with a low InAs content could be kept small enough to prevent the formation of misfit dislocations to sufficient thickness that the SPSL could be characterized with x-ray diffraction and other techniques. In contrast, the growth of InAs/GaAs SPSL on InP showed degradation of the RHEED patterns at such small thicknesses (a few hundred Ångstroms) that characterization would have been extremely difficult or impossible with conventional methods. The growth temperature was kept relatively low-390°C, to reduce strain induced surface roughening.

By growing SPSLs such as $(InAs)_1(GaAs)_7$, which is only 14% InAs, on a GaAs substrate, we could grow thick enough layers for characterization. This would allow us to determine the structural perfection (variations from perfect periodicity, variations from integer layers) and the effects of variability in the MBE growth process and calibration on the superlattice structural properties.

This approach was partially successful. It did allow the growth low dislocation SPSL layers with good RHEED patterns up to approximately 17% InAs content at thicknesses of more than 300 nm. [5] This thickness is considerably above the thickness usually associated with the onset of strain relief by dislocation generation in random alloys of these compositions, which suggests that the SPSL are more resistant to dislocation generation and strain induced surface roughening than corresponding random alloys. This conclusion was strengthened the observation that, for a given InAs average content, the thickness of the individual InAs layers in the superlattice period affected the RHEED pattern degradation. For example, an $(InAs)_{1.15}(GaAs)_7$ superlattice roughened at a thickness of 68 nm, whereas an $(InAs)_1(GaAs)_6$ superlattice, containing nearly the same InAs content, still exhibited a fairly good RHEED pattern when growth was terminated at 300 nm

The growth of GaAs at low temperatures was also investigated, using migration-enhanced epitaxy (MEE). This was done to understand the role of low temperatures and surface adatom mobility on epitaxial growth, and because others had reported MEE to be an effective means of improving superlattice properties. This line of investigation eventually became the most productive of this project. [1-3, 4, 6]

Difficulties in SPSL characterization eventually caused the abandonment of their growth. X-ray diffraction double crystal rocking curves were our primary tool, done on campus. We observed a zeroth order superlattice peak on most samples, and also recorded first order satellite peaks on a few samples. The results were consistent with material with the correct superlattice period, and the low InAs-content SPSL had line widths similar to the best SPSL reported at the time. The linewidth of the zeroth order peak correlated with the roughening observed with RHEED. Because of the very small period, SPSL peaks are widely separated, making them difficult to detect using a double crystal rocking curve apparatus. Furthermore, the small thickness of the layers caused the diffracted intensity of the peaks other than the first order to be very small, near or below the limits of our equipment. We established collaborations with two other laboratories (one of them was EDTL, Ft. Monmouth; the other has significantly more sophisticated x-ray apparatus than ours) and sent them our SPSL samples, but they were unable to observe more than the zeroth order peaks. Since more peaks are required in order to fit the rocking curve to theory and extract the interfacial mixing and roughening and the deviation from perfect periodicity, our characterization was limited.

Because of the difficulty encountered in growing and characterizing SPSL material, emphasis was shifted to the low temperature growth of doped GaAs material for use in the base of HBTs, where we felt more progress could be made. This led to the discovery of techniques, using MEE, of growing heavily Be-doped material at unusually low temperatures while retaining sufficient mobility and minority carrier lifetime to yield operating HBTs with usable gain, yet avoiding the diffusion of Be during growth. [1, 6] Although carbon doping is now believed to have advantages over Be in reducing diffusion, there are still some difficulties in the growth of C-doped material for HBTs. Thus our work on the low temperature growth of Be-doped GaAs may yet find applications.

In parallel, processing for AlGaAs/GaAs HBTs was developed, which allowed us to fabricate operating HBTs. The early stages of this development led to a collaboration with M/A Com, Inc., which is continuing. Our HBT devices are presently processed by a Penn State PhD student previously supported on this contract, who is now working part time at M/A Com while completing his thesis.

To summarize our technical results, we have

- grown InAs/GaAs SPSL on InP and GaAs and determined their surface roughening behavior with thickness and InAs content;
- correlated x-ray linewidths with RHEED observations of roughening;
- developed methods to use migration-enhanced epitaxy to grow doped GaAs on (111) and (100) substrates, with material on both orientations having good mobilities;
- studied the properties of low-temperature conducting GaAs, determining Schottky barrier heights; and
- applied the migration-enhanced epitaxy technique to the low temperature growth of Be-doped base material for HBTs with usable gain and no Be diffusion during growth.

Perhaps the most significant results are not represented completely by the publications and talks. This was the first major funding for a new research group, formed only one year before the beginning of the contract period. As a result, it funded not only the direct technical efforts, but also provided the principal support for five PhD students, and partial support for two other students. It resulted in the establishment of an HBT processing capability at Penn State and led to the collaboration with M/A Com, which in turn established their HBT process. The ability to grow and process HBTs, acquired with the support of this project, has enabled our research group to win a grant to develop integrated optoelectronic receivers incorporating HBTs. We also have an ongoing collaboration with a U. S. epitaxial wafer supplier to help them develop doping processes for HBTs, which would not have been possible without the capabilities for HBT growth developed in this program.

Two students will be receiving PhD degrees within the coming year based largely on work funded by this project. A third will be receiving a PhD this year on work which grew out of this project. One MS degree was granted which, although not directly funded by this project, was made possible by the MBE lab principally supported by this project. Several other students have benefited for shorter periods from support from this contract as they performed specific tasks for it, such as x-ray diffraction or parts of the HBT process development.

Report of Inventions: none

Manuscripts Published or Submitted:

1) "Low Temperature Migration Enhanced Epitaxy of AlGaAs/GaAs Base Material," Kai Zhang, Der-woei Wu, Jianming Fu, D. L. Miller, Mike Fukuda, and Yong-Hoon Yun, submitted to Appl. Phys. Lett.

2) "Effect of LT-GaAs on Epitaxial Al/GaAs Schottky Diode Characteristics," Kai Zhang, D. L. Miller, MRS Symposium Proceedings vol. 262-F2, 1992 (in press).

3) "Plasma Hydrogenation Studies on Low Temperature MBE-Grown GaAs," O. S. Nakagawa, Kai Zhang, W. K. Chung, D. L. Miller, and S. Ashok, MRS Symposium Proceedings vol. 262-F2, 1992 (in press).

4) "Migration Enhanced Epitaxy of Doped GaAs on (111)B and (100) GaAs Substrates," Jianming Fu, Kai Zhang, D. L. Miller, J. Vac. Sci. Technol. B10 (2), 779 (1992).

5) "Study of $(InAs)_m(GaAs)_n$ Short-Period Superlattice Layers Grown on GaAs Substrates by Molecular Beam Epitaxy," Jung-Geau Jang, Jianming Fu, Kai Zhang, and D. L. Miller, J. Vac. Sci. Technol. B10 (2), 772 (1992).

6) "Conducting Be-doped GaAs by Low Temperature Molecular Beam Epitaxy," K. Zhang, S. S. Bose, D. L. Miller, and N. Pan, Journal of Electronic Materials 21 (2), 187 (1992).

Talks and Presentations:

"A Study of Electrical Properties of LT-GaAs Grown by Molecular Beam Epitaxy and Migration Enhanced Epitaxy," Kai Zhang and D. L. Miller, submitted to Symposium D of the Spring MRS meeting, 1993.

"Photoreflectance Spectroscopy of Low Temperature MBE GaAs," Wen-yen Hwang, Kai Zhang, and D. L. Miller, presented at the 1992 Electronics Materials Conference, Boston, June 1992.

"Low Temperature Migration Enhanced Epitaxy of AlGaAs/GaAs Base Material," Kai Zhang, Der-woei Wu, Jianming Fu, D. L. Miller, Mike Fukuda, and Yong-Hoon Yun, presented at the 1992 Electronics Materials Conference, Boston, June 1992.

"Effect of LT-GaAs on Epitaxial Al/GaAs Schottky Diode Characteristics," Kai Zhang, D. L. Miller, presented at the Materials Research Society Spring 1992 Meeting.

"Plasma Hydrogenation Studies on Low-Temperature MBE-Grown GaAs," O. S. Nakagawa, Kai Zhang, W. K. Chung, D. L. Miller, and S. Ashok, presented at the Materials Research Society Spring 1992 Meeting.

"Study of the Fermi Level Position of LT GaAs Using Franz-Keldysh Oscillations," H. Shen, M. Dutta, W. Chang, and Kai Zhang, presented at the Fall 1991 Materials Research Society Meeting.

"Migration Enhanced Epitaxy of Doped GaAs on (111)B and (100) GaAs Substrates," Jianming Fu, Kai Zhang, D. L. Miller, presented at the U. S. Molecular Beam Epitaxy Workshop, Austin, TX, September 1991.

"Study of $(InAs)_m(GaAs)_n$ Short-Period Superlattice Layers Grown on GaAs Substrates by Molecular Beam Epitaxy," Jung-Geau Jang, Jianming Fu, Kai Zhang, and D. L. Miller, presented at the U. S. Molecular Beam Epitaxy Workshop, Austin, TX, September 1991.

"Conducting Be-doped GaAs by Low Temperature Molecular Beam Epitaxy," K. Zhang, S. S. Bose, D. L. Miller, and N. Pan, presented at the 1991 Electronic Materials Conference, June 19-21, Boulder, CO.

Scientific Personnel Supported in Full or in Part During This Project:

This project has, during its funded period, provided the majority of support for five students (Mr. Jianming Fu, Mr. Brian Luther, Mr. Der-Woei Wu, Mr. Kai Zhang, and Ms. Wen-Huei Li) and partial support for two others (Mr. Wen-yen Hwang, Mr. Jung-Geau Jang). It was the first major funded project for this research group, and was instrumental in getting these students started on their PhD research. In addition, it supported the Principal Investigator to the extent of 33% of the academic year salary for two years, providing some reduction of the teaching load during that time. The personnel supported is summarized below.

Person	position	support, period	present status
Dr. David Miller	Faculty	9/89-9/91 12 wks salary each year (33%)	principal investigator
Mr. Jianming Fu	PhD stud.	9/89-8/91 1/2-time asst.	PhD expected 12/93
Mr. Wen-yen Hwang	PhD stud.	9/90-12/90 1/4-time asst. 1/90-9/92 supplies, mat. 9/92-12/92 1/4-time asst.	PhD expected 12/94
Mr. Jung-Geau Jang	PhD stud.	9/90-6/91 1/2-time asst.	PhD student (another group)

Mr. Brian Luther	PhD stud.	1/91-8/91 supplies, mater. 9/91-6/92 1/4-time asst.	PhD expected 1995
Mr. Der-Woei Wu	PhD stud.	9/89-6/91 1/2 time asst. 8/91-6/92 1/2-time asst.	PhD expected 12/93
Mr. Kai Zhang	PhD stud.	9/90-12/92 1/2 time asst.	PhD expected 6/93
Ms. Wen-Huei Li	MS stud.	9/90-12/92 lab fees, supplies, mat.	MS granted 6/92