AD-A205 175

(2)

REPORT DOCUMENTATION PAGE

1b. RESTRICTIVE MARKINGS DTIC FILE COPY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
1988

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 89-0092

6a. NAME OF PERFORMING ORGANIZATION
Department of Electrical Engrg.
Columbia University in the City of New York

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Same as 8a

6c. ADDRESS *(City, State, and ZIP Code)*
New York, NY 10027

7b. ADDRESS *(City, State, and ZIP Code)*
Same as 8B

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
Air Force Office of Scientific Research

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-88-0126

8c. ADDRESS *(City, State, and ZIP Code)*
Building 410
Bolling Air Force Base

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61102F	2306	B1	

11. TITLE *(Include Security Classification)*
MBE growth and characterization of metastable semiconductors for infrared detector applications

12. PERSONAL AUTHOR(S) Professor Wen I Wang

13a. TYPE OF REPORT Annual Technical Report

13b. TIME COVERED FROM 2/1/88 TO 10/31/88

14. DATE OF REPORT *(Year, Month, Day)* November 25, 1988

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION Read and accepted report on 12 Dec 88; also requested of P.I., Prof. Wang, that in all future reports he include an abstract of the report as well as multiple copies.
C.W. Litton, P.M., AFOSR/NE.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

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

DTIC
S ELECTE D
23 FEB 1989
E

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL Litton

22b. TELEPHONE *(Include Area Code)* (202) 767-4931

22c. OFFICE SYMBOL NE

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

AFOSR-TR- 8 9 - 0 0 8 2

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
ANNUAL REPORT

for period February 1 to October 31, 1988

GRANT NO. 88-0126

entitled

"MBE GROWTH AND CHARACTERIZATION OF METASTABLE SEMICONDUCTORS FOR INFRARED DETECTOR APPLICATIONS"

by
Professor Wen I. Wang, Principal Investigator
Department of Electrical Engineering
Columbia University
New York, New York 10027

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

Annual Research Report for AFOSR 88-0126 "Molecular beam epitaxial growth and characterization of metastable compound semiconductors for infrared detector applications"

The first year of research performed under this contract started on February 1, and end on October 31, 1988. The emphasis of our research under this program is to obtain device quality narrow gap materials.

During this initial phase of research, all the fundamental work necessary for future achievement of high quality metastable materials has been completed. This work includes the growth of all the various buffer layer materials such as InAs, InSb, GaSb, and AlSb, the calibration of the Auger system for quick feedback of alloy composition, and the in-situ RHEED oscillation calibration of growth rate.

During this buffer layer studies, we found that the growth of InAs and AlSb are compatible in the temperature range of 450-500 °C. AlSb/InAs/AlSb double-barrier resonant tunneling structures have therefore been grown and measured. Peak-to-valley ratios of 1.8:1 at room temperature and 9:1 at 77K have been measured. Most importantly, the small effective mass of InAs makes it possible to demonstrate quantum effects in a 24 nm well, the longest coherent distance ever reported for double-barrier tunneling structures. We have also estimated that an AlSb/InAs resonant tunneling transistor can significantly outperform similar devices based on AlGaAs/GaAs. On the basis of simple circuit modeling, InAs/AlSb transistors appears to have a cutoff frequency in excess of 100 GHz. This work will be published in Applied Physics Letters in December, 1988. A copy of the paper is enclosed. All the work supported by this contract is concerned with narrow-gap materials for infrared detector applications. It now turns out that some of these narrow-gap materials such as InAs and InSb are an excellent choice for future high speed devices, as demonstrated by our double-barrier tunneling experiment.

One side accomplishment during this buffer layer study was the discovery of a universal C(8x2) reconstructed surface for III-V compound semiconductors. This reconstruction has not been reported before for GaSb. GaSb surfaces usually show a threefold reconstruction. We have noticed that GaAs surfaces show a twofold reconstruction under a wide range of substrate temperature and As-to-Ga flux ratio. As soon as we add Al to GaAs, i.e., AlGaAs, the surface changes to threefold reconstruction. With 30 years of surface science history, there has been no model for the threefold reconstruction. Whatever the model for threefold reconstruction might be, it is obvious to us that it is a disordered surface and shows up whenever there is an element with a large sticking coefficient or low surface mobility, such as Al or Sb. Our work shows that at high substrate temperatures, metal-stablized twofold reconstruction, i.e., C(8x2), can always be obtained. We have discovered that this C(8x2) structure is common to all III-V compounds, suggesting that bond-pairing is a universal reconstruction mechanism. Also, in the past the rocking curve of single crystal GaSb grown by MBE was very broad and was found to be sensitive to the Sb-to-Ga flux ratio. This is likely related to the long surface lifetime of Sb. We now think that growth at temperatures and flux ratios such that a C(8x2) structure could be generated may be optimal conditions, and optimized buffer GaSb would certainly be beneficial for the overgrowth of GeSn alloys. We are presently in the process of writing up a paper to report this work.

Metastable α-Sn has been grown on InSb buffer layers which were in turn grown on InSb substrates. We found that at a growth temperature of 90 °C α-Sn could still be produced. This is higher than the 70 °C reported previously by R.F.C. Farrow et al. One likely reason is that previous studies did not use an InSb buffer layer. Our two-growth-chamber system allows us to grow an InSb buffer layer in one chamber and a Sn layer in another chamber, which is essential for future work.

$Ge_{0.75}Sn_{0.25}$ alloy films have been grown at 180 °C on InP substrates. The GeSn alloy surface shows a streaky (1x1) reconstruction, indicating the epitaxial films being a single crystal. X-ray diffraction measurements are being carried out on these samples, and we expect to obtain results in the near future. $Ge_{0.5}Sn_{0.5}$ has been grown on GaSb substrates. During initial stage of crystal growth, a streaky (1x1) pattern was observed; but quickly the RHEED showed the diffused background scattering, which is an indication of the coexistence of some β-Sn. Later on the data from x-ray diffraction confirmed the presence of β-Sn in such samples. Therefore our experiments seem to indicate that it is difficult to incorporate 50% Sn into Ge. Transmission measurements are being carried out in collaboration with Dr. Reuben Collins and Zak Schlesinger at IBM T.J. Watson Research Center. The initial results on $Ge_{0.5}Sn_{0.5}$ grown on GaSb substrates showed very weak transmission, which may be due to the free carrier absorption in the thick substrate material. The samples are now being thinned, and further experiments are planned for the near future.

Applied Physics Letters

Resonant tunneling in AlSb/InAs/AlSb double-barrier heterostructures

L. F. Luo, R. Beresford, and W. I. Wang
Department of Electrical Engineering and Microelectronics Sciences Laboratories, Columbia University, New York, New York 10027

(Received 5 July 1988; accepted for publication 3 October 1988)

We report the first observations of resonant tunneling in the AlSb/InAs material system, with a maximum peak-to-valley current ratio of 1.8:1 at room temperature and 9:1 at 77 K. The large AlSb/InAs barrier height of 1.8 eV for electrons and high-mobility InAs will be advantageous in device applications. In particular, the small electron effective mass in InAs makes it possible to demonstrate quantum effects in a 24 nm well, the longest coherence distance reported for double-barrier tunneling structures. We estimate that an AlSb/InAs resonant tunneling transistor can significantly outperform similar devices based on AlGaAs/GaAs.

Resonant tunneling through a heterostructure quantum well was first studied by Tsu and Esaki,[1] and by Chang *et al.*[2] Heterojunction resonant tunneling transistors (RTT's) have been discussed by Jogai and Wang,[3] Capasso and Kiehl,[4] and Bonnefoi *et al.*[5] These devices and proposals are based on tunneling through thin semiconductor layers, from "continuum" states in the emitting electrode to a confined state in the quantum well.

Because tunneling is a fast process, such devices offer the potential for high speed. To realize that potential in practical devices will require much larger barrier heights than have been achieved to date. For the best performance, the highest possible barriers are required. Among all nearly lattice-matched binary III-V and II-VI combinations, AlSb/InAs provides the largest barrier for electrons of 1.8 eV.[6-9] Although AlSb/InAs/GaSb was recently used for a hot-electron transistor,[10] this material system has not been used previously in tunneling applications.

A large peak-to-valley ratio is important for the resonant tunneling applications envisaged. In RTT's, the collector-emitter current is controlled by the potential of the base, which acts to move the confined state of the quantum well into or out of alignment with the occupied energy levels in the emitter. Thus, a high peak-to-valley ratio of RT diode current corresponds to a large fractional change in current for a voltage swing on the order of the width of the tunneling electron distribution. Since the absolute current can be quite large, high values of transconductance are possible. As discussed by Jogai *et al.*,[11] the highest frequency of operation of resonant tunneling diodes as microwave power sources is directly proportional to the negative differential conductance, which again increases with the peak-to-valley ratio.

Besides high peak-to-valley ratio, a practical three-terminal RT device has at least the following other requirements: low parasitic resistance and capacitance, a base region (quantum well) thick enough to make reliable electrical contact to it, and a high output resistance.

Although AlAs/GaAs offers a $\Gamma - \Gamma$ barrier of about 1 eV, the $\Gamma - X$ barrier is only 0.2 eV. In contrast, AlSb/InAs offers a $\Gamma - \Gamma$ barrier of 1.8 eV and a $\Gamma - X$ barrier of 1.2 eV. The high barrier and the small effective mass in InAs mean that quantum confinement can be achieved in wider wells, making base contacts feasible. Furthermore, the Fermi level in InAs is pinned in the conduction band, so that any metal/*n*-InAs contacts will be perfectly ohmic. Finally, in InAs the electron mobility and saturation velocity are 4–5 times larger than in GaAs, leading to lower parasitic base resistance and better high-frequency performance.

The material studied here was grown by molecular beam epitaxy (MBE)[12,13] on (100) oriented *n*-type GaAs or InAs substrates in Columbia's three-chamber system. Resonant tunneling was observed in both cases; however, the current-voltage (*I-V*) characteristics of structures grown on InAs were better than those of structures grown on GaAs, as expected. Conceivably, a graded layer of GaInAs could improve the structures grown on GaAs. In these samples, a 500 nm InAs buffer layer and an AlSb/InAs/AlSb double-barrier structure are sandwiched between two 200-nm-thick InAs electrodes. Figure 1 shows the band line-up and a typical structure, with 2.5 nm AlSb barriers sandwiching a 16.8 nm InAs quantum well.

Diodes were fabricated by evaporating approximately 600 nm of Au/Ge through a shadow mask. The 10-mil-diam dots served as a mask during the chemical etching that defined mesa diodes. The samples were indium bonded to glass slides for probing.

Current-voltage characteristics were measured at room temperature and at 77 K. Curve tracer photographs for a representative device are shown in Fig. 2. A peak-to-valley

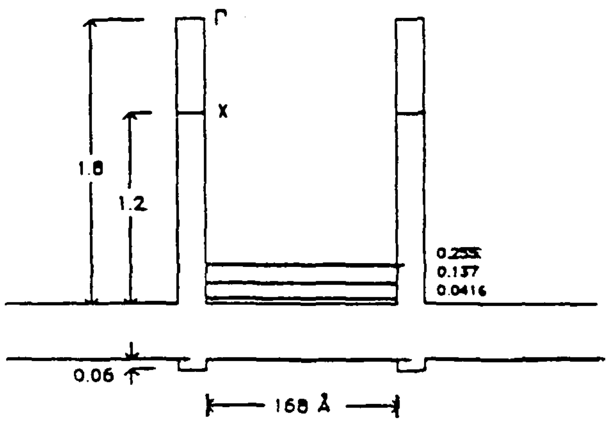

FIG. 1. Resonant tunneling structure with InAs well and electrodes and AlSb barriers. Band offsets and energies of the first three confined states in the quantum well are shown (in eV).

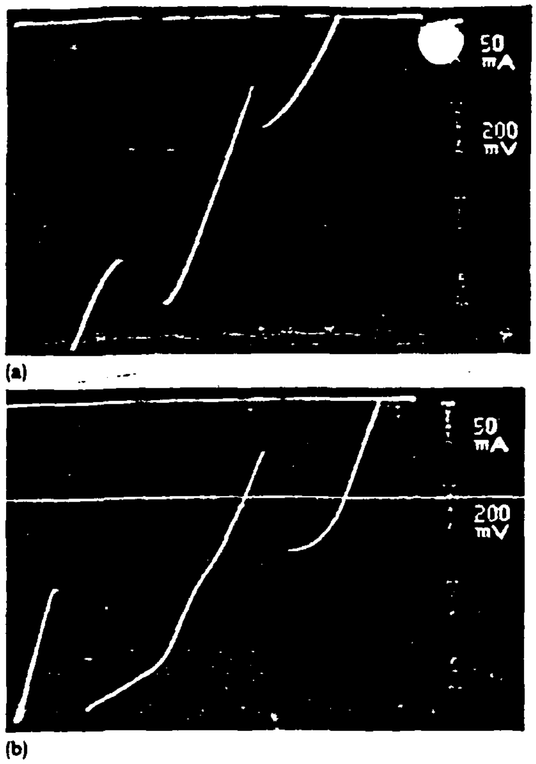

FIG. 2. Curve tracer photographs of double-barrier heterostructure *I-V* characteristics (a) at room temperature and (b) at 77 K. The quantum well is 16.8 nm, the barriers 2.5 nm.

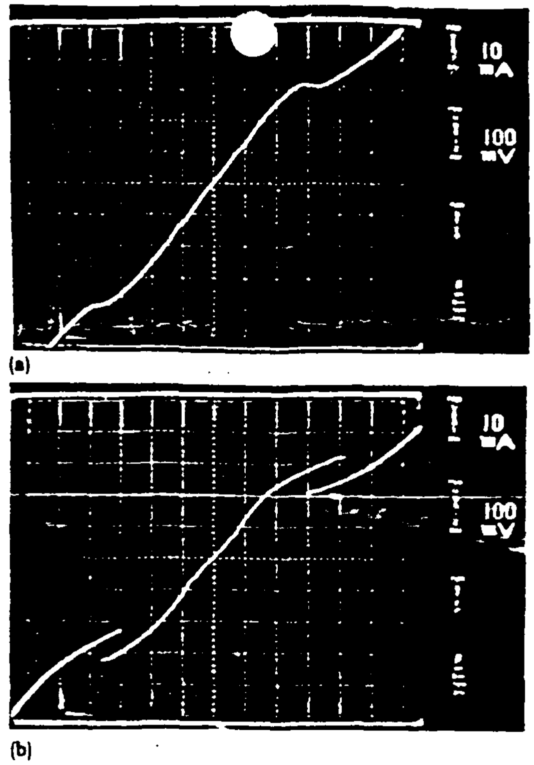

FIG. 3. Resonant tunneling characteristics of a 24 nm quantum well measured (a) at room temperature and (b) at 77 K. The barrier widths are 3.9 nm.

ratio of 1.8:1 is observed at room temperature; this figure improves to 9:1 at 77 K. The peak current density is 355 A/cm^2. Some devices showed asymmetry in their *I-V* characteristics, with the resonant peak appearing at much higher voltages for reverse bias (dot negative with respect to the substrate) compared to positive bias. The asymmetry is consistent with MBE growth of a highly resistive interface between the substrate and the epitaxial layer. Figure 3 shows resonant tunneling in a 24 nm well, measured at room temperature and at 77 K.

The position of the first resonant tunneling peak in the current was observed at 77 K for five diodes, with well widths of 15.1, 16.8 (two samples), and 24 nm (two samples). These data are plotted in Fig. 4, along with calculated curves of energy level versus well width for several barrier heights. The calculation uses the conventional two-band model of electron disperson in the band gap, with the *E-k* curvature fit to the AlSb conduction-band effective mass at the band edges. The nonparabolicity of the InAs conduction band is taken into account. The experimentally determined peak positions were corrected for voltage drops in the electrode series resistances by evaluating the *I-V* slopes at high biases. Considering the difficulty in making these measurements of device resistance, we believe that the data shown in the figure are consistent with a barrier height (conduction band offset) of approximately 1.8 eV.

The high barrier of 1.8 eV and the high electron mobility InAs quantum well make this material system attractive for high-performance RTT's. To estimate transistor performance, we have considered published data and a simplified equivalent circuit for RTT operation. The RTT is inherently a high-capacitance and high-current device; the thin tunneling barriers contribute a large parallel-plate capacitance and permit large current flow on or near resonance. The most important fundamental limitations on transistor performance are expected to be the quantum well (base) series resistance, the capacitance of the emitter barrier, and the intrinsic (transit time) delay of the tunneling electrons. Limitations due to parasitic components in a practical device structure (additional series resistances and extrinsic base capacitance) are not considered here.

The parallel-plate capacitance of 2.5 nm AlSb tunnel barriers is 50 fF/μm^2, assuming a dielectric constant of 14.4 for AlSb. As a basis for comparison of base resistance, the intrinsic base resistance in a state-of-the-art AlGaAs/GaAs heterojunction bipolar transistor is 1.7 Ω (Ref. 14) for a 70 nm base width and 30 μm^2 emitter. Considering the higher electron saturation velocity in InAs, we estimate that a 20 nm InAs base of the same lateral geometry will have approximately a 1.2 Ω spreading resistance. In contrast, an AlGaAs/GaAs RTT would require an even thinner base, and thus a base resistance at least 10 times higher. The base-emitter time constant of a 30 μm^2 emitter AlSb/InAs RTT is estimated to be 1.2 $\Omega \times$ 1.5 pF = 1.8 ps, vs 13 ps or more for an AlGaAs/GaAs device.

As discussed by Jogai *et al.*,[11] the transit-time delay of tunneling electrons has been estimated to be less than 0.1 ps. Those authors calculated *I-V* characteristics for an AlGaAs/GaAs RTT structure (2 nm barriers), from which a very large room-temperature transconductance of about 20 mS/μm^2 can be deduced. The current density at the first resonance peak in this calculation is 2×10^5 A/cm^2, much

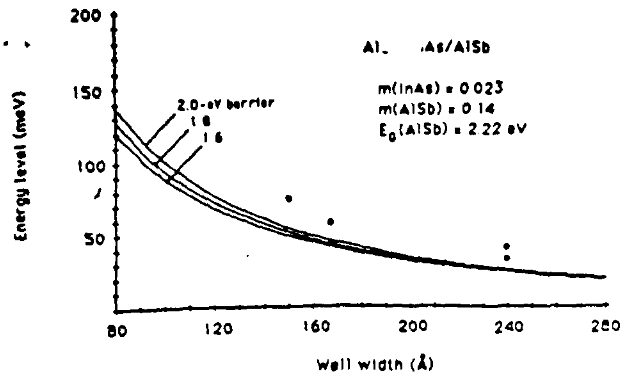

FIG. 4. First confined state energy level vs quantum well width. Solid curves show calculations using the two-band model; dots are the experimentally determined points.

larger than that typically observed in resonant tunneling diodes. Even with such a high value of transconductance, the capacitance associated with the transit-time delay ($g_m \tau$) is only 2 fF/μm^2, much smaller than the emitter barrier capacitance. As a result, the transistor cutoff frequency $g_m/2\pi C_{tot}$ will be dominated by the barrier capacitance. For the example RTT with 50 fF/μm^2 barrier capacitance and 20 mS/μm^2 transconductance, the cutoff frequency is approximately 64 GHz, comparable to the 55 GHz of the AlGaAs/GaAs HBT in Ref. 14. Given the much larger barrier height in the AlSb/InAs system, we believe that an additional factor of two greater transconductance may reasonably be achieved, providing a cutoff frequency in excess of 100 GHz. An AlGaAs/GaAs RTT would certainly fail to reach this performance level due to its large input time constant, even if the large transconductance were achieved.

Thus, on the basis of simple circuit modeling, resonant tunneling transistors appear to have the potential for high-frequency performance. We have demonstrated resonant tunneling in the AlSb/InAs system, achieving a peak-to-valley current ratio of 9:1. The high barrier of about 1.8 eV and the high electron mobility and small effective mass in the InAs quantum well are important improvements over the AlGaAs/GaAs system for prospective device applications of resonant tunneling.

We greatly appreciate the support of the Office of Naval Research and the additional support from the Air Force Office of Scientific Research.

[1] R. Tsu and L. Esaki, Appl. Phys. Lett. 22, 562 (1973).
[2] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. 24, 593 (1974).
[3] B. Jogai and K. L. Wang, Appl. Phys. Lett. 46, 167 (1985).
[4] F. Capasso and R. A. Kiehl, J. Appl. Phys. 58, 1366 (1985).
[5] A. R. Bonnefoi, D. H. Chow, and T. C. McGill, Appl. Phys. Lett. 47, 888 (1985).
[6] W. I. Wang and Frank Stern, J. Vac. Sci. Technol. B 3, 1280 (1985).
[7] J. Tersoff, Phys. Rev. Lett. 56, 2755 (1986).
[8] C. Tejedor, J. M. Calleja, F. Meseguer, E. E. Mendez, C. A. Chang, and L. Esaki, Phys. Rev. B 32, 5303 (1985).
[9] J. Menendez, A. Pinczuk, D. J. Werder, J. P. Valladares, T. H. Chiu, and W. T. Tsang, Solid State Commun. 61, 703 (1987).
[10] A. F. J. Levi and T. H. Chiu, Appl. Phys. Lett. 51, 984 (1987).
[11] B. Jogai, K. L. Wang, and K. W. Brown, Appl. Phys. Lett. 48, 1003 (1986).
[12] A. Y. Cho, Thin Solid Films 100, 291 (1983).
[13] J. H. English, A. C. Gossard, H. L. Stormer, and K. W. Baldwin, Appl. Phys. Lett. 50, 1826 (1987).
[14] P. M. Asbeck, M. F. Chang, K.-C. Wang, D. L. Miller, G. J. Sullivan, N. H. Sheng, E. Sovero, and J. A. Higgins, IEEE Trans. Electron Devices ED-34, 2571 (1987).