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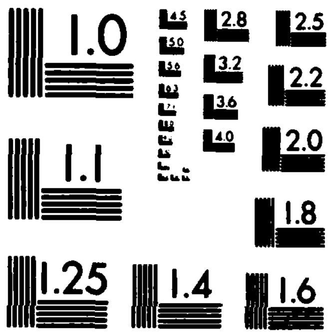
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FUNDAMENTAL ASPECTS OF HETEROJUNCTION BIPOLAR TRANSISTOR TECHNOLOGY

FINAL REPORT FOR THE PERIOD
June 15, 1983 through June 30, 1986

CONTRACT NO. DAAG29-83-C-0020

Prepared for

U.S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

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JULY 1986

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) MRDC41137.7FR	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 20454.5-EL
6a. NAME OF PERFORMING ORGANIZATION Rockwell International Corporation Microelectronics Research and Development Center 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) 1049 Camino Dos Rios Thousand Oaks, CA 91360	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Research Office 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DAAG29-83-C-0020
8c. ADDRESS (City, State and ZIP Code) P.O. Box 12211 Research Triangle Park, NC 27709	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT NO.
11. TITLE (Include Security Classification) FUNDAMENTAL ASPECTS OF HETEROJUNCTION BIPOLAR TRANSISTOR TECHNOLOGY	

12. PERSONAL AUTHOR(S)
Miller, D.L. and Asbeck, P.M.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Report	FROM 06/15/83 TO 06/30/86	JULY 1986	8

16. SUPPLEMENTARY NOTATION
The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Heterojunction bipolar transistor (HBT) Beryllium diffusion Molecular beam epitaxy (MBE)

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

Fundamental aspects of heterojunction bipolar transistor (HBT) technology were investigated, including Be diffusion in MBE growth, the effects of epitaxial structure variations on HBT technology, effects of selected device processing methods on HBT performance, and modelling of HBT devices and ring oscillators. A summary of major results in each of these areas is given, and publications resulting from this contract are listed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code) | 22c. OFFICE SYMBOL

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

FUNDAMENTAL ASPECTS OF HETEROJUNCTION BIPOLAR TRANSISTOR TECHNOLOGY

1.0 FOREWORD

This is the final report for Army Research Office contract DAAG29-83-C-0020, "Fundamental Aspects of Heterojunction Bipolar Transistor Technology", covering the period 6/15/83 to 6/30/86. The report contains a summary and discussion of the main findings of this research project.

2.0 TECHNICAL REPORT

2.1 Statement of Problem

The heterojunction bipolar transistor (HBT) is an exciting candidate for future high-speed digital and analog applications. The goal of this investigation was to provide a firm scientific and technological basis for enhanced high-speed HBT performance, and to demonstrate this performance in ring-oscillator circuits. The approach was to investigate some important aspects of HBT structure growth by molecular beam epitaxy (MBE), to study ion implantation into HBT structures for purposes of device processing, and to model the performance of HBT structures. Information obtained from these investigations was to be used to design optimized HBT devices consistent with the realities of MBE material growth and ion implantation processing. High-speed ring-oscillators were to be developed to test the high-speed potential of these devices.

The technical areas investigated were:

- o The diffusion of Be and its effect on HBT performance.
- o The effect of epitaxial structure variations on HBT performance.
- o The effects of selected device processing methods on HBT performance.
- o Modeling of HBT device and ring-oscillator circuits, and the demonstration of high-speed operation in ring-oscillators.

The results in each of these areas are summarized in the following section.

2.1 The Diffusion of Be and its Effect on HBT Performance

Beryllium is the most commonly used p-type dopant in GaAs and AlGaAs MBE due to its high sticking coefficient, high activation, and relatively low diffusion coefficient. Because the layer dimensions of HBT structures are often 500Å or less, even very small amounts of Be diffusion during MBE growth or subsequent device processing can be significant for device performance.

We have used Secondary Ion Mass Spectrometry (SIMS) to investigate the diffusion of Be in MBE GaAs and AlGaAs during the growth process and during implantation anneals. SIMS analysis was performed by Evans Associates, San Mateo, CA. Samples were grown which contained abrupt distributions of Be at various concentrations. SIMS data was correlated with device electrical properties. Using these experiments, we discovered or confirmed that:

- Be diffusion can occur during MBE growth over distances which are significant for HBT devices.
- Two types of Be redistribution occur: a bulk-like diffusion and an anisotropic carry forward or surface-riding effect.
- Diffusion is faster in AlGaAs than GaAs, and faster at higher Be concentrations.
- The characteristic length of the carry forward phenomenon depends on alloy composition and doping.
- HBT gain can be affected by Be diffusion into the AlGaAs emitter, forming a barrier to electron injection.

A majority of these points are discussed in the publication "Be Redistribution During Growth of MBE GaAs and AlGaAs", D. L. Miller and P. M. Asbeck, Journal of Applied Physics, Vol. 57, page 6, March 15, 1985.

2.3 The Effect of Epitaxial Structure Variations on HBT Performance

A number of structural variations, i.e., variations in the thickness, doping, or composition of layers of the MBE-grown structure, were investigated with the goal of understanding the contributions of several factors to device performance. The main results were:

- Grading of the emitter-base junction composition decreases the forward bias required to inject electrons into the base due a reduction in the barrier formed as a result of the GaAs-AlGaAs conduction band offset.
- Using an undoped "setback" region between the p-type GaAs base region and the n-type AlGaAs emitter can compensate for Be diffusion, and improve device gain, although the setback must be carefully matched to the degree of Be diffusion.
- Heavy base doping, up to 1×10^{19} /cm3, can be used to reduce base resistance and base contact resistance if care is taken to avoid Be diffusion.
- Many structural variations are masked by processing-induced degradation of device gain.
- InGaAs strained layers may be incorporated in the base of AlGaAs/GaAs HBTs.

The last point, the use of InGaAs in the base of HBTs, warrants further mention. InGaAs has several advantages over GaAs for the base of an HBT. It has a smaller bandgap so that a larger barrier to hole injection may be obtained for a given AlGaAs emitter composition; alternatively, a lower Al content be be used for a given barrier height to reduce deep level in the AlGaAs. Furthermore, strained layers of InGaAs have been shown to have the light hole band split off from, and higher in energy than, the heavy hole band. Thus, the light hole sub-band will be populated preferentially, and it may be possible to achieve higher hole mobilities in this way. Finally, it may be possible to dope InGaAs more heavily than GaAs.

HBTs were fabricated with InGaAs strained bases, doped as heavily as 5 x 1019 /cm3 with Be. These showed acceptable gain and operated in ring-oscillators with a propagation delay of 19 ps, which was then a record for HBTs.

Some of our InGaAs-base HBT work was reported in the paper, "AlGaAs/InGaAs/GaAs Strained-Layer Heterojunction Bipolar Transistors by Molecular Beam Epitaxy", G. J. Sullivan, P. M. Asbeck, M. F. Chang, D. L. Miller, and K. C. Wang, Electronic Letters, Vol 22 (10), page 419, 1986.

2.4 The Effects of Selected Device Processing Methods on HBT Performance

Oxygen implantation to reduce base-collector capacitance, and flash annealing of Be implants to reduce Be diffusion were the main processing methods studied. Oxygen was implanted through the base of AlGaAs/GaAs and AlGaAs/InGaAs/GaAs HBTs in order to render a portion of the collector semi-insulating. The areas implanted are the so-called extrinsic base regions, those regions outside the emitter contact. This process succeeded in reducing the base-collector capacitance significantly, which was observed in ring-oscillator performance. A variation of this technique was responsible in part for the reduction of ring-oscillator propagation delay to below 17 ps in our latest HBT circuits. The oxygen implant procedure is summarized in greater detail in the publication "GaAs/(GaAl)As Heterojunction Bipolar Transistors with Buried Oxygen - Implanted Isolation Layers", P. M. Asbeck, D. L. Miller, R. J Anderson, and F. H. Eisen, IEEE Electronic Device Letters, Vol. EDL 5 (8), page 310, 1984.

The flash annealing process uses a heat lamp to rapidly heat water to anneal an implant. Shorter times at anneal temperatures lead to a dramatic reduction in Be diffusion while attaining high implant activation. This was an essential step in developing our HBT process with an implanted base contact.

2.5 Modeling of Devices and Circuits

Modeling of devices and circuits was done to determine the effect of device structures and circuit parameters on performance, and to develop an accurate model for HBTs. SPICE modeling of ring-oscillators was done, which agreed well with performance data from HBT ring-oscillators made in our laboratory, lending confidence to the modeling of HBT circuits. Device models were used to investigate the effects of base degeneracy and bandgap shrinkage at high doping on collector currents. It was found that incorporation of these effects was necessary for accurate device modeling. Electron current in graded emitter-base junctions was modeled to investigate emitter-base capacitance under forward-bias conditions. It was found that effects due to bandgap grading and electron/hole overlap are both important to an accurate calculation of the capacitance, which is 2 to 5 times larger than given by a simple depletion estimate.

A portion of this work is scheduled to appear in the paper, "Electron Current in GaAs/AlGaAs Graded Heterojunction Bipolar Transistors", P. M. Asbeck, D. L. Miller and H. Kromer, accepted for publication in IEEE Transaction on Electronic Devices.

2.6 Summary and Applications of this Research

Important new work has been done under this contract in the areas of Be diffusion during MBE growth, oxygen implantation in HBTs for capacitance reduction, and the use of strained layer InGaAs for HBTs. In addition, a large amount of information, which is perhaps less significant in a fundamental scientific sense, but which contributes greatly to the technology of HBT devices and circuits has been developed along the way to demonstration of higher speed HBT devices. This is illustrated by the steady decrease in ring-oscillator propagation delay from 52 ps in the first semi-annual progress report to our current best result of 17 ps. The information gained in this contract has been central to this improvement in device performance.

3.0 LIST OF PUBLICATIONS AND TECHNICAL REPORTS

In addition to the semi-annual technical reports required under this contract, the following publications were generated:

Publications

"Nonthreshold Logic Ring Oscillators Implemented with GaAs/(GaAl)As Heterojunction Bipolar Transistors", P. M. Asbeck, D. L. Miller, R. J. Anderson, H. D. Hou, R. Dening, and F. Eisen, IEEE Electr. Dev. Lett., EDL-5 (5), 181, (1984).

"GaAs/(GaAl)As Heterojunction Bipolar Transistors with Buried Oxygen - Implanted Isolation Layers", P. M. Asbeck, D. L. Miller, R. J. Anderson, and F. H. Eisen, IEEE Electr. Dev. Lett., EDL-5 (8), 310, (1984).

"Be Redistribution During Growth of MBE GaAs and AlGaAs", D. L. Miller and P. M. Asbeck, J. Appl. Phys., 57, (6), 1816, (1985).

"AlGaAs/InGaAs/GaAs Strained-Layer Heterojunction Bipolar Transistors by Molecular Beam Epitaxy", G. J. Sullivan, P. M. Asbeck, M. F. Chang, D. L. Miller, K. C. Wang, Electr. Lett., 22, 419, (1986).

"Electron Current in GaAs/AlGaAs Graded Heterojunction Bipolar Transistors", P. M. Asbeck, D. L. Miller and H. Kroemer, accepted for publication in IEEE Trans. Electr. Dev.

4.0 PARTICIPATING SCIENTIFIC PERSONNEL

During the three years of this contract, the following scientific personnel participated directly in the research effort:

P. M. Asbeck
M. F. Chang
R. T. Chen
I. Golecki
L. Lamar
D. L. Miller
G. Sullivan
K. C. Wang
L. A. Wood

No advanced degrees were earned by any participants while employed on this project.

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