GaAs-GaN Wafer Fusion

and the

n-AlGaAs/p-GaAs/n-GaN Double Heterojunction Bipolar Transistor

Sarah M. Estrada

This dissertation is dedicated to my parents,

who deserve this and so much more,

to Ruthie, Pumpkin, Isamay, Ryan,

and of course

to Evelyn.

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Curriculum Vitae

Sarah M. Estrada

EDUCATION

- University of California at Santa Barbara, Ph.D. in Materials, Sept. 2004
- University of California at Santa Barbara, Certificate for Graduate Program in Management Practice, Sept. 2004
- University of California at Berkeley, B.S. in the double major of Chemical Engineering and Materials Science and Engineering, Dec. 1995

AWARDS & AFFILIATION

- Presidential Management Fellowship, U.S. Office of Personnel Management, 2004-2006
- Graduate Teaching Fellowship in K-12 Education (GK-12), National Science Foundation, 2003-2004
- Graduate Student Gold Award, Materials Research Society, Fall 2003
- Pre-doctoral Fellowship for Minorities, Ford Foundation, 1999-2002
- Membership in Sigma Xi, Alpha Chi Sigma, Materials Research Society, Minerals, Metals, & Materials Society, Institute of Electrical & Electronics Engineers, American Physical Society, American Association for the Advancement of Science

WORK HISTORY

- Program Management Analyst, Space and Missile Systems Center, Los Angeles Air Force Base, starting 08/2004
- NSF Graduate Teaching Fellow, California NanoSystems Institute, Santa Barbara, California, 07/2003-06/2004
- Graduate Student Researcher, Materials Department, University of California at Santa Barbara, 07/1998-06/2003
- Graduate Student Mentor of Apprentice Researchers, Calif. NanoSystems Institute, Santa Barbara, CA, 07/2001-08/2003
- Teaching Assistant, Materials Department, University of California at Santa Barbara, 09/1997-06/1998
- Engineer, Process Engineering Department, Dow Chemical Company, Freeport, Texas, 01/1996-07/1997
- Undergraduate Research Assistant, Chemical Engineering Dept., University of California at Berkeley, 08/1994-05/1995
- Three Student Co-op Internships, Dow Chemical Company, Freeport, Texas & Midland, Michigan, 01/1994-08/1995

PUBLICATIONS (available in .pdf format at http://sarah.optimism.us/engineering)

- S. Estrada, J. Champlain, C. Wang, A. Stonas, L. Coldren, S. DenBaars, U. Mishra, & E. Hu, Wafer-fused n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistor with uid-GaAs Base-Collector Setback, Materials Research Society Symposium Proceedings, vol. 798, Y10.20, 2004.

- S. Estrada, E. Hu, & Umesh Mishra, "n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistor: the First Transistor Formed via Wafer Fusion," in GaN-based Materials and Devices: Growth, Fabrication, Characterization, and Performance, vol. 33, Selected Topics in Electronics and Systems, R. Davis & M. S. Shur, Eds., 1st ed. World Scientific Publishing Co. (River Edge, New Jersey), ISBN 981 238 844 3, pp. 265-284, 2004.

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- J. Jasinski, Z. Liliental-Weber, S. Estrada, & E. Hu, Microstructure of GaAs/GaN interfaces produced by direct wafer fusion, Applied Physics Letters, vol. 81, no. 17, pp. 3152-4, 2002.

- J. Jasinski, Z. Liliental-Weber, S. Estrada, & E. Hu, Transmission Electron Microscopy Studies of Electrical Active GaAs/GaN Interface Obtained by Wafer Bonding, Materials Research Society Symposium Proceedings, vol. 722, K7.15, 2002.

PRESENTATIONS

- Invited talk: Wafer-fused n-AlGaAs/p-GaAs/n-GaN Transistors, Laserion International Workshop on Microfabrication, Nanostructured Materials, & Biotechnology, Schloss Ringberg/Tegernsee, Germany, 06/04.
- Wafer-fused n-AlGaAs/p-GaAs/n-GaN Transistors with Base-Collector Setback, California NanoSystems Institute (CNSI) & Center for Nanoscience (CeNS) Workshop, Santa Barbara, CA, 03/04.
- Let's Explore Applied Physical Science (LEAPS), National Science Foundation GK-12 Annual Meeting, Washington, DC, 03/04.
- Wafer-fused n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistors with uid-GaAs Base-Collector Setback, Materials Research Society Fall Meeting, Boston, MA, 12/03.
- Direct Wafer Bonding of AlGaAs/GaAs/GaN HBTs, Solid-State Lighting & Display Center Workshop, Santa Barbara, CA, 11/03.
- Materials Engineering of the Wafer-fused AlGaAs-GaAs-GaN Heterojunction Bipolar Transistor, CAM Physics Meeting, Merida, Mexico, 10/03.
- Wafer-fused nAlGaAs-pGaAs-nGaN Heterojunction Bipolar Transistors, Electronic Materials Conference, Salt Lake City, UT, 06/03.
- The First AlGaAs/GaAs/GaN Heterojunction Bipolar Transistor Fabricated via Wafer Fusion, Student Research Conference & Graduate Fair, Tempe, AZ, 04/03.
- Wafer-fused nAlGaAs-pGaAs-nGaN Heterojunction Bipolar Transistor, Solid-State Lighting & Display Center Workshop, Santa Barbara, CA, 12/02.
- A Wafer-fused n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistor (HBT), Materials Research Society Fall Meeting, Boston, MA, 12/02.
- Lattice-mismatched GaN/GaAs Heterodevices via Wafer Fusion, Solid State Technology Review, Santa Barbara, CA, 11/02.
- The First AlGaAs/GaAs/GaN Double Heterojunction Bipolar Transistor via Wafer Fusion, Electronic Materials Conference, Santa Barbara, CA, 06/02.
- GaAs/GaN Diodes Wafer-Fused at 500oC Electronic Materials Conference, Notre Dame, IN, 06/01.
- Wafer Fusion of GaAs/GaN Semiconductors for Electronic Devices, Conference of Ford Fellows, Irvine, CA, 10/00.
- Wafer Fusion of GaAs/GaN Heterostructures, Electronic Materials Conference, Denver, CO, 06/00.

Abstract

Sarah M. Estrada

GaAs-GaN Wafer Fusion

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n-AlGaAs/p-GaAs/n-GaN

Double Heterojunction Bipolar Transistor

This dissertation describes the n-AlGaAs/p-GaAs/n-GaN heterojunction bipolar transistor (HBT), the first transistor formed via wafer fusion. The fusion process was developed as a way to combine lattice-mismatched materials for high-performance electronic devices, not obtainable via conventional all-epitaxial formation methods. Despite the many challenges of wafer fusion, successful transistors were demonstrated and improved, via the optimization of material structure and fusion process conditions. Thus, this project demonstrated the integration of disparate device materials, chosen for their optimal electronic properties, unrestricted by the conventional (and very limiting) requirement of lattice-matching.

By combining an AlGaAs-GaAs emitter-base with a GaN collector, the HBT benefited from the high breakdown voltage of GaN, and from the high emitter injection efficiency and low base transit time of AlGaAs-GaAs. Because the GaAs-GaN lattice mismatch precluded an all-epitaxial formation of the HBT, the GaAs-

GaN heterostructure was formed via fusion. This project began with the development of a fusion process that formed mechanically robust and electrically active GaAs-GaN heterojunctions. During the correlation of device electrical performance with a systematic variation of fusion conditions over a wide range (500-750°C, 0.5-2hours), a mid-range fusion temperature was found to induce optimal HBT electrical performance. Transmission electron microscopy (TEM) and secondary ion mass spectrometry (SIMS) were used to assess possible reasons for the variations observed in device electrical performance. Fusion process conditions were correlated with electrical (I-V), structural (TEM), and chemical (SIMS) analyses of the resulting heterojunctions, in order to investigate the trade-off between increased interfacial disorder (TEM) with low fusion temperature and increased diffusion (SIMS) with high fusion temperature.

The best dc device results (I_C~2.9 kA/cm^2 and β~3.5, at V_{CE}=20V and I_B=10mA) were obtained with an HBT formed via fusion at 600°C for 1hour, with an optimized base-collector design. This was quite an improvement, as compared to an HBT with a simpler base-collector structure, also fused at 600°C for 1hour (I_C~0.83 kA/cm^2 and β~0.89, at V_{CE}=20V and I_B=10mA). Fused AlGaAs-GaAs-GaAs HBTs were compared to fused AlGaAs-GaAs-GaN HBTs, demonstrating that the use of a wider bandgap collector ($E_{g,GaN} > E_{g,GaAs}$) did indeed improve HBT performance at high applied voltages, as desired for high-power applications.

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