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RESEARCH ON SEMICONDUCTOR HETEROSTRUCTURES(U)
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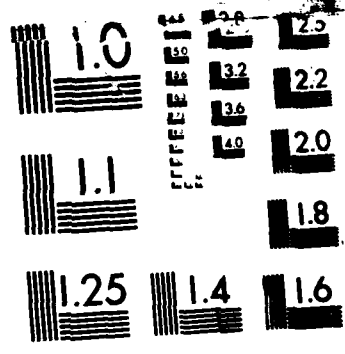
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Abstract

A wide diversity of topics related to various new properties of semiconductor heterostructures were investigated, ranging from an intense occupation with the problem of the band lineup at semiconductor heterojunctions, to the problem of the MBE growth of GaAs/Ge alloys and the structure of these alloys, with a variety of topics in between. The development, under this contract, of the C-V profiling technique for the determination of heterojunction band offsets has since then emerged as the most reliable technique of offset determination and which has widely displaced the quantum well absorption technique as the preferred method of offset determination. Below-gap light emission from staggered-lineup heterojunctions has become unusually timely with the discovery that the (Al,Ga)As/GaAs heterosystem is a staggered-lineup system. Several other topics investigated also contributed significantly to an advancement of the understanding of semiconductor heterostructures.

Research on Semiconductor Heterostructures

Final Report

on

ONR Contract N00014-77-C-0430

by

Herbert Kroemer

Department of Electrical and Computer Engineering,

University of California,

Santa Barbara, CA 93106

Abstract

A wide diversity of topics related to various new properties of semiconductor heterostructures were investigated, ranging from an intense occupation with the problem of the band lineup at semiconductor heterojunctions, to the problem of the MBE growth of GaAs/Ge alloys and the structure of these alloys, with a variety of topics in between. The development, under this contract, of the C-V profiling technique for the determination of heterojunction band offsets has since then emerged as the most reliable technique of offset determination and which has widely displaced the quantum well absorption technique as the preferred method of offset determination. Below-gap light emission from staggered-lineup heterojunctions has become unusually timely with the discovery that the (Al,Ga)As/GaAs heterosystem is a staggered-lineup system. Several other topics investigated also contributed significantly to an advancement of the understanding of semiconductor heterostructures.

1) Summary

The research conducted under this contract over a number of years concerned itself with a wide diversity of topics, all related to various new properties of semiconductor heterostructures. The topics ranged from an intense occupation with the problem of the band lineup at semiconductor heterojunctions, to the problem of the MBE growth of GaAs/Ge alloys and the structure of these alloys, with a variety of topics in between.

The large diversity of topics studied had been deliberate: One of the explicit purposes of this research was to explore a wide range of previously insufficiently studied semiconductor phenomena of potentially high payoff, with the intent to select for a more in-depth study those that appeared promising, and to drop those for which that was not the case.

Several of the topics led to extensive further investigations, some of them to new lines of research that have since then expanded greatly. One of the first item of intensive investigation, remaining important throughout the entire contract, was the development of the C-V profiling technique for the determination of heterojunction band offsets [2, 5, 8, 18, 21]. It has since then emerged as the most reliable technique of offset determination and which has widely displaced the quantum well absorption technique as the preferred method of offset determination. This particular topic was part of a broader intense occupation with the understanding of heterojunction band offsets, both from the theoretical and the experimental point-of-view [8, 11, 12, 15, 17].

A second research topic first studied under this contract, below-gap light emission from staggered-lineup heterojunctions [7, 16], has since then become unusually timely with the discovery that the (Al,Ga)As/GaAs heterosystem is a staggered-lineup system, a development that is beginning to have a large impact on the development of shorter-wavelength (Al,Ga)As/GaAs multi-quantum-well lasers.

Our work on (211)-oriented (Al,Ga)As/GaAs superlattices under this contract [23, 24], together with our earlier abortive attempt to use the (110) orientation for GaP-on-Si growth [3] was the first deliberate departure from the essentially universal use of the crystallographic (100) orientation since the early days of MBE technology; it has recently stimulated others to consider crystallographic orientations other than the traditional (100) orientation.

A minor "sideline project" under this contract, on then-unconventional designs of heterostructure bipolar transistors [10, 22] has since then become widely accepted.

There were several additional topics investigated in less depth: (i) The theory of degenerate space charge layers at abrupt isotype heterojunctions [4]. (ii) The problem of the interface connection rules for effective-mass wave functions at hetero-interfaces [6, 9]. (iii) The nucleation and growth stoichiometry of InAs on GaAs [14].



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Fairly extensive and very interesting work on the growth and structure of GaAs/Ge alloys [13, 19, 20] had to be broken off, not for lack of interesting results, but because the MBE growth turned out to introduce excessive Ge contamination into the growth chamber, making it incompatible with the numerous other projects for which the MBE system was needed. If a dedicated system (and more resources) had been available, it would have been pursued further.

Finally, one project never got off the ground, for lack of an individual capable of pursuing something as difficult and speculative: An investigation of some of the potentially fascinating properties of broken-gap heterojunctions. It has been chosen as one of the central topics of a new ONR contract.

2) Publications

The following published papers describe work that was supported at least partially under this contract.

- [1] H. Kroemer, Wu-Yi Chien, H. C. Casey, Jr., and A. Y. Cho, "Photocollection Efficiency and Interface Charges of MBE-grown Abrupt p(GaAs)-N($\text{Al}_{0.33}\text{Ga}_{0.67}$)As Heterojunctions," *Appl. Phys. Lett.* **33** (#8), 749-751, Oct. 1978.
- [2] H. Kroemer, Wu-Yi Chien, J. S. Harris, and D. D. Edwall, "Measurement of Isotype Heterojunction Barriers by C-V Profiling," *Appl. Phys. Lett.* **36**, (#4), 295-297, Feb. 1980.
- [3] H. Kroemer, K. J. Polasko, and S. C. Wright, "On the (110) Orientation as the Preferred Orientation for the Molecular Beam Epitaxial Growth of GaAs on Ge, GaP on Si, and Similar Zincblende-on-Diamond Systems," *Appl. Phys. Lett.* **36** (#9), 763-765, May 1980.
- [4] H. Kroemer, "Analytic Approximations for Degenerate Accumulation Layers in Semiconductors, with Applications to Barrier Lowering in Isotype Heterojunctions," *J. Appl. Phys.* **52** (#2), 873-878, Feb. 1981.
- [5] H. Kroemer and Wu-Yi Chien, "On the Theory of Debye Averaging in the C-V Profiling of Semiconductors," *Solid-State Electronics* **24** (#7), 655-660, July 1981.
- [6] H. Kroemer and Q.-G. Zhu, "On the Interface Connection Rules for Effective-Mass Wave Functions at an Abrupt Heterojunction Between Two Semiconductors with Different Effective Mass," *J. Vac. Sci. Technol.* **21** (#2), 551-553, July/Aug. 1982.
- [7] H. Kroemer and G. Griffiths, "Staggered-Lineup Heterojunctions as Sources of Tunable Below-Gap Radiation: Operating Principle and Semiconductor Selection," (*IEEE Electron Dev. Lett.* **EDL-4** (#1), 20-22, Jan. 1983.
- [8] H. Kroemer, "Critique of Two Recent Theories of Heterojunction Lineups," *IEEE Electron Dev. Lett.* **EDL-4**, (#2), 25-26, Feb. 1983.
- [9] Q.-G. Zhu and H. Kroemer, "Interface Connection Rules for Effective-Mass Wave Functions at an Abrupt Heterojunction Between Two Different Semiconductors," *Phys. Rev. B* **27** (#6), 3519-3527, Mar. 1983.
- [10] H. Kroemer, "Heterostructure Bipolar Transistors: What Should We Build?," *J. Vac. Sci. Technol.* **B1** (#2), 126-130, Apr./June 1983.
- [11] H. Kroemer, "Heterostructure Devices: A Device Physicist Looks at Interfaces," *Surf. Sci.* **132**, 543-576, 1983.
- [12] H. Kroemer, "Rebuttal to 'Response to 'Critique to Two Recent Theories of Heterojunction Lineups''," *IEEE Electron Dev. Lett.* **EDL-4** (#10), 365, Oct. 1983.

- [13] I. Banerjee, H. Kroemer, and D. W. Chung, "Observation of Phase Separation in $(\text{Ge}_2)_x(\text{GaAs})_{1-x}$ Alloys Grown by Molecular Beam Epitaxy," *Matls. Lett.* 2 (#3), 189-193, Feb. 1984.
- [14] B. R. Hancock and H. Kroemer, "Relation Between Growth Conditions and Reconstruction on InAs During Molecular Beam Epitaxy Using an As_2 Source" *J. Appl. Phys.*, 55 (#12), 4239-4243, June 1984.
- [15] H. Kroemer, "Barrier Control and Measurements: Abrupt Semiconductor Heterojunctions," *J. Vac. Sci. Technol.* B2 (#3), 433-439, July/Sept. 1984.
- [16] E. J. Caine, S. Subbanna, H. Kroemer, J. L. Merz, and A. Y. Cho, "Staggered-Lineup Heterojunctions as Sources of Tunable Below-Gap Radiation: Experimental Verification," *Appl. Phys. Lett.* 45, 1123-1125, Nov. 1984.
- [17] H. Kroemer, "Theory of Heterojunctions: A Critical Review," in *Molecular Beam Epitaxy and Heterostructures* (L. L. Chang and K. Ploog, eds.), NATO ASI Series E (Applied Sciences), Vol. E 87, pp. 331-379, Martinus Nijhoff Publishers, Dordrecht 1985.
- [18] H. Kroemer, "Determination of Heterojunction Band Offsets by Capacitance-Voltage Profiling through Nonabrupt Isotype Heterojunctions," *Appl. Phys. Lett.* 46 (#5), 494-496, March 1985.
- [19] I. Banerjee, D. W. Chung, and H. Kroemer, "Properties of $(\text{Ge}_2)_x(\text{GaAs})_{1-x}$ Alloys Grown by Molecular-Beam Epitaxy," *Appl. Phys. Lett.*, 46 (#5), 494-496, March 1985.
- [20] I. Banerjee, H. Kroemer, and D. W. Chung, "Summary Abstract: Properties of $(\text{Ge}_2)_x(\text{GaAs})_{1-x}$ Alloys Grown by Molecular Beam Epitaxy" *J. Vac. Sci. Technol.* B3 (#2), 538-539, Mar./Apr. 1985.
- [21] D. I. Babic and H. Kroemer, "The Role of Nonuniform Dielectric Permittivity in the Determination of Heterojunction Band Offsets by C-V Profiling Through Isotype Heterojunctions," *Solid State Electronics* 28 (#10), 1015-1017, Oct. 1985.
- [22] H. Kroemer, "Two Integral Relations Pertaining to the Electron Transport Through a Bipolar Transistor with a Non-uniform Gap in the Base Region," *Solid State Electronics*. 28 (#11), 1101-1103, Nov. 1985.
- [23] S. Subbanna, H. Kroemer and J.L. Merz, "Growth and Selected Properties of GaAs Layers and GaAs/(Al,Ga)As Superlattices with the (211)A and (211)B Orientations," *J. Appl. Phys.* 59 (#2) 488-494, Jan. 1984.
- [24] S. Subbanna, H. Kroemer and J.L. Merz "Extended Abstract: Growth and Selected Properties of GaAs Layers and GaAs/(Al,Ga)As Superlattices with the (211)A and (211)B Orientations," *J. Vac. Sci. Technol.* B4, 515-516, Mar./Apr. 1986

The following manuscript has been accepted for publication and is currently in the press.

- [25] H. Kroemer, "Band offsets at hetero-interfaces: Theoretical basis, and review, of recent experimental work," Proc. 2nd Int. Conf. (Yamada Conference) on Modulated Semiconductor Structures (MSS-II), Kyoto, Japan, Sept. 1985, to appear in Surf. Sci. 172, 1-8 (1986).

3) Scientific Personnel Supported under this Contract, And Degrees Earned

3.1) Principal Investigator and Visiting Faculty

Professor Herbert Kroemer, Principal Investigator:

throughout entire contract (June 1977 - Aug. 1985).

Professor Brian Ridley, Visiting Faculty member from University of Essex,
United Kingdom: Apr. - July 1981.

3.2) Post-Doctoral Research Associates

Dr. Indrajit Banerjee: Summer 1982 - Summer 1984.

Dr. Ernie J. Caine: Winter 1983 - End of contract (Aug. 1985).

Dr. Grant Griffiths: Fall 1981 - Spring 1983.

Dr. Beth Stoeckly: Fall 1977 - Spring 1978.

Dr. Parvez Uppal: Fall 1984 - End of contract (Aug. 1985).

3.3) Research Assistants working towards a PhD Degree

Mr. Wu-Yi Chien: Beginning of Contract (June 1977) - Summer 1980; received PhD in
Fall 1980.

Mr. Seshadri Subbanna: Winter 1984 - End of contract (Aug. 1985); received MS in Fall
1985; continuing towards PhD under follow-up ONR contract..

Mr. Gerard Sullivan, Spring 1979; continued under different ONR contract;
received PhD in Summer 1983.

Mr. Steven L. Wright, Summer 1977; continued under an ARO contract;
received PhD in Spring 1982.

3.4) Research Assistants working towards an MS Degree

Mr. Dubravko I. Babic, Summer 1983 - Fall 1984, received MS in Fall 1984.

Mr. Domingo Figueredo, Fall 1980 - Spring 1981, received MS in Spring 1981.

Mr. Bruce R. Hancock, Winter 1980 - Fall 1982, received MS in Fall 1982;
Continued under different contracts (AFOSR and SRC),
received PhD in Spring 1985.

Mr. Mark Mondry: Summer 1982 - Summer 1985; received MS in Fall 1985.

Mr. Kenneth J. Polasko, Fall 1978 - Spring 1980, received MS Fall 1980.

Mr. David Rogers, Fall 1979 - Spring 1980; terminated by PI.

Mr. Bao-Sung Yeh, Fall 1980; terminated by PI.

3.5) Individuals Contributing to this Research without Financial Support

Professor James L. Merz, Advisor and contributor to photoluminescence work.

Dr. Don Chung, Post -Doctoral Research Associate in Dept. of Chemical and Nuclear Engineering; Contributor to transmission electron microscopy.

Dr. Khalid Mohammed; Post -Doctoral Research Associate under Prof. Merz; frequent contributor to photoluminescence work.

Dr. Qui-Gao Zhu; Visiting Scholar; Contributor to theoretical work.

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