REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0525

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 15, 2000	Final Technical (4/1/1999-3/31/2000)

4. TITLE AND SUBTITLE
(DURIP-99) Atomic Force Microscope and Pulsed Ti-Sapphire Laser to Pursue Device Research at Virginia Microelectronic Center

5. FUNDING NUMBERS
Grant #F49620-99-1-0149
PO #FQ8671-9900927

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8. PERFORMING ORGANIZATION REPORT NUMBER
Final Technical for #528459

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
801 N. Randolph St., Room 732
Arlington, VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

20001023 062

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*
A Digital Nanoscan III Atomic Force Microscope (AFM) and a roughing station have been purchased and installed. The latter was made possible by a discount negotiated with Digital Inc. The AFM acquired is of high resolution type with a maximum of 15 by 15 micron scan area and equipped with Electric Force Microscopy (EFM), Magnetic Force Microscopy (MFM) features and atmospheric scanning tunneling microscopy as well. Moreover, the instrument has been outfitted with optional equipment facilitating imaging of biological samples (liquid cell) and a sample holder for cross-sectional AFM.

The scope has been in operation for more than a year, and has been and is heavily used by graduate and undergraduate students in Electrical Engineering and Physics. The scope was also used for a graduate class in laboratory techniques in the Physics Department.
The scope has been primarily used for investigating surface features of GaN. As grown surfaces as well as etched surfaces for defect analysis have been imaged. We have already obtained crucial defect information on HVPE, MBE and MOCVD samples. We are currently making good progress toward developing samples for EFM development as well as using EFM on unknown samples for checking the polarity of the films. The scope gets used for quick imaging of Si (5 5 12) surfaces for Prof. Baski's research in Physics.

The roughing station is a BOC Edwards (EXP Combined Outfit Pumping Station) which sports a dry mechanical pump and a turbo pump. This system eliminated the use of time consuming liquid nitrogen traps in six vacuum systems as well as speeding up the process of roughing the systems down to low enough pressure before the resident pumps take over. We are already saving on nitrogen use while benefiting from reduced turn around time and better vacuum to be obtained.

14. SUBJECT TERMS
GaN, MBE, MOCVD

15. NUMBER OF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

DURIP 99 Final Report for

Atomic Force Microscope & Pulsed TI-Sapphire Laser to Pursue Device Research at Virginia Microelectronic Center (F49620-99-1-0149)

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Summary

A Digital Nanoscan III Atomic Force Microscope (AFM) and a roughing station have been purchased and installed. The latter was made possible by a discount negotiated with Digital Inc. The AFM acquired is of high resolution type with a maximum of 15 by 15 micron scan area and equipped with Electric Force Microscopy (EFM), Magnetic Force Microscopy (MFM) features and atmospheric scanning tunneling microscopy as well. Moreover, the instrument has been outfitted with optional equipment facilitating imaging of biological samples (liquid cell) and a sample holder for cross-sectional AFM. The scope has been in operation for more than a year, and has been and is heavily used by graduate and undergraduate students in Electrical Engineering and Physics. The scope was also used for a graduate class in laboratory techniques in the Physics Department.

The scope has been primarily used for investigating surface features of GaN. As grown surfaces as well as etched surfaces for defect analysis have been imaged. We have already obtained crucial defect information on HVPE, MBE and MOCVD samples. We are currently making good progress toward developing samples for EFM development as well as using EFM on unknown samples for checking the polarity of the films. The scope gets used for quick imaging of Si (5 5 12) surfaces for Prof. Baski's research in Physics.

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Training and Development in regard to AFM

We have extensively trained 2 graduate students and 3 undergraduates on the Digital Nanoscope Atomic Force Microscope (see table below). The undergraduates primarily characterize the surface morphology of the GaN samples produced on a daily basis in Dr. Morkoç' research laboratory, whereas the graduate students and research associates develop the more demanding applications such as electric force microscopy.

In addition to the GaN research, the AFM is used as teaching tool for two upper-level laboratory courses, Senior Physics Laboratory (PHYS 450) and Materials Characterization Lab (PHYS 550). These courses typically have enrollments of 5 to 10 students each and have laboratories that introduce the students to AFM and allow them to perform standard sample characterization. The students are very interested to obtain hands-on experience with research-level instrumentation that is now becoming a standard research tool in many physical and chemical laboratories.

Undergraduate Students		**Graduate Students & others**	
Dickinson, John	Physics	Jones, Keith	Physics, M.S. Engineering, Ph.D.
Jekauc, Igor	Physics/ EE	Sun, Albert	Physics, M.S.
Kerwath, Leonne	Physics	Dr. Yun	research associate

Publications resulting directly from the use of the AFM

1.Hadis Morkoç "Growth of GaN/AlGaN Modulation Doped and Quantum Well Structures and the Associated Polarization effects", International Conference on Silicon Carbide and Related Materials, October 10-15, 1999, Research Triangle Park, NC. The proceedings papers is by Hadis Morkoç, M. A. Reshchikov, A. Baski, and M. I. Nathan*, "GaN Quantum Dots on Sapphire and Si substrates" Proceedings of the International Conference on Silicon Carbide and Related Materials, October 10-15, 1999, Research Triangle Park, NC USA. Materials Science Forum, Trans Tech Publications, Vol. 338-342 - Part 2, pp. 1453-1455, 2000, eds. C. H. Carter, Jr., R. P. Devaty, and G. S. Rohrer.

2. M. A. Reshchikov, J. Cui, F. Yun, A. Baski, M. I. Nathan, R. Molnar, and Hadis Morkoç, "GaN based quantum dot heterostructures", Spring MRS meeting, April 24-27, 2000, San Francisco. To be published in Proc. of Spring MRS meeting, in press.

3. J. Cui, and A. Sun, M. Reshichkov, F. Yun, A. Baski, and H. Morkoç, "Preparation of Sapphire for High Quality III-Nitride Growth", MRS Internet Journal - The URL for the front page is http://nsr.mij.mrs.org/5/7/.

4. P. Visconti, K. M. Jones, M. A. Reshchikov, R. Cingolani, H. Morkoç, and R. Molnard, "Investigation of defects in GaN by photo-electrochemical and hot wet etching" Appl. Phys. Lett., pending.

5. P. Visconti, K. M. Jones, M. A. Reshchikov, F. Yun, R. Cingolani, H. Morkoç, S. S. Park and K. Y. Lee, "Characteristics of Free Standing Hydride Vapor Phase Epitaxy Grown GaN with very low defect concentration", Appl. Phys. Lett., pending.

6. M. A. Reshchikov, P. Visconti, and H. Morkoç, "Blue photoluminescence activated by surface states in GaN", Appl. Phys. Lett., pending.

Abstracts of selected publications made possible by the instrument

Characteristics of Free Standing Hydride Vapor Phase Epitaxy Grown GaN with very low defect concentration

Abstract

A free standing 300 μm thick GaN template grown by hydride vapor phase epitaxy (HVPE) has been characterized for its structural and optical properties using X-ray diffraction, defect delineation etch followed by imaging with atomic force microscopy (AFM), and variable temperature photoluminescence (PL). The Ga-face and the N-face of the c-plane GaN exhibited a wide variation in terms of the defect density. The defect concentrations on Ga and N-faces were about $5x10^5$ cm^{-2} for the former and about $1x10^7$ cm^{-2} for the latter. The full width at half maximum (FWHM) of the symmetric (0002) X-ray diffraction peak was 69 and 160 arcsec for the Ga and N-faces, respectively. That for the asymmetric (10-14) peak was 103 and 140 arcsec for Ga and N-faces, respectively. The donor bound exciton linewidth as measured on the Ga and N-face (after a chemical etch to remove the damage) is about 1 meV each at 10K. Instead of the commonly observed yellow band, this sample displayed a green band, which is centered at about 2.44 eV.

Investigation of defects in GaN by photo-electrochemical and hot wet etching

Abstract

Defects in GaN layers grown by hydride vapor phase epitaxy have been investigated by photo electrochemical (PEC) etching, and by wet etching in hot H_3PO_4 acid and molten KOH. Threading vertical wires (i.e. whiskers) and hexagonal-shaped etch pits are formed on the etched sample surfaces by PEC and wet etching, respectively. Using atomic force microscopy, we find the density of "whisker-like" features to be $2x10^9$ cm^{-2}, the same value found for the etch pit density on samples etched with both H_3PO_4 and molten KOH. This value is comparable to the dislocation density obtained in similar samples with TEM, and is also consistent with the results of Youtsey et al.

GaN based quantum dot heterostructures

Abstract

GaN dots have been grown on c-plane sapphire and (111) Si substrates by reactive molecular beam epitaxy. A new method involving two-dimensional growth followed by a controlled annealing during which dots are formed was employed. Due the dot nature and large dot density, relatively high luminescence efficiencies were obtained on both substrates. Single layer dots were used for AFM analysis whereas 30 layer dots were used for photoluminescence experiments. AlN barrier layers, some too thick for mechanical interaction, some thin enough for vertical coupling were used. Strong polarization effects lead to a sizeable red shift, which depends on the size of the dots.

Particulars with respect to the acquisition of our Nanoscope IIIa Station and Multimode Atomic Force Microscope

Company: Digital Instruments, 112 Robin Hill Rd., Santa Barbara, CA 93117

Price: $ $109,709.25., F.O.B. Santa Barbara, CA

An **atomic force microscope (AFM)** was purchased with necessary options to measure topographic, magnetic, and electrical surface properties of a variety of samples. Two leading AFM manufacturers were asked to perform **site demonstrations** of their instruments in the research floor of the Virginia Microelectronics Center where the AFM is now located. Digital Instruments showed its Multimode Nanoscope on May 4/5'99, and Thermomicroscopes demonstrated its CP on May 11/12'99. We have chosen Digital for its superior quality of images, owing to a better piezo-controlled stage, and ease with which the software can be used. The scope was delivered in June 1999 with a follow up installation and training session. Prof. A. Baski of the VCU Physics department was very instrumental in the acquisition and operation, and training of the students and postdoctoral fellow. The scope is now very heavily used by her group as well that of Morkoc's, and has become a critical component of our laboratory.

Quote for the roughing station

Send Order To: **BOC Edwards** Quotation # BOCVCU31
c/o Pascal Technologies, Inc. Date: August 12, 1999
P.O. Box 8146
Fredericksburg, VA 22404

PHONE 800/367-2919 FAX 540/891-2233

Quotation for: Hadis Morkoç Terms: Net 30
Virginia Commonwealth University Quote valid for 30 days
601 W. Main St. Current Delivery: 6-8wks ARO
Richmond, VA 23284-3072 FOB Point: Shipping Point

Phone 804-827-3765 Fax 804-828-4269

Item	Qty	Description		Unit Price
1	1	EXP Combined Outfit Pumping Station Includes: EXT 255H Turbo Pump, 220 l/s N2 Flange Type DN100ISO-K EXC120 Controller ESDP12 Scroll Pump, 8.8 cfm Mounting to frame, dimensions 27.5"H x 11"W x 23"L No accessories – Backing Pump ACX 250 Air Cooler Electrical – 110-120V, 50/60Hz (Part # T459-06-022)	$ 11,180.70	
			Sub Total	**$13,872.00**
Option:				
2	1	Casters for Frame		**$ 171.00**
3	1	ISO100 to NW50 Adapter		**$ 185.00**
			Total	*$14,228.00*

Biographical Sketch of the Principal Investigator

Hadis Morkoç

Founders Professor, Department of Electrical Engineering and Physics Department
Virginia Commonwealth University, 600 West Main Street, Richmond, VA 23284
Phone: 804 827-3765
Fax: 804 828-4269
email: hmorkoc@vcu.edu

Education

1973 - 1975	Ph.D. degree in Electrical Engineering, Cornell University
1971 - 1973	Ph.D. candidate in Electrical Engineering, Michigan State University
1968 - 1969	MS degree in Electrical Engineering, Istanbul Technical University
1964 - 1968	BS degree in Electrical Engineering, Istanbul Technical University

Professional experience

1997-present: Founders Professor of Electrical Engineering and Physics Department, Virginia Commonwealth University, Richmond, VA.
1995 – 1998:University Resident Research Professor, Wright Laboratory, Wright Patterson Air Force Base, OH.
1987 – 1988:Distinguished Visiting Scholar, Jet Propulsion Laboratory and California Institute of Technology, Pasadena, CA.
1978 – 1997:Assistant and Associate Professor of Electrical Engineering and Research Associate Professor of Coordinated Science Laboratory, Univ. of Illinois, Urbana-Champagne, IL.
1986 – 1997:Graduate Faculty, Dept. of Physics and Material Science and Engineering, Univ. of Illinois, Urbana-Champagne, IL.
1978 – 1979:Resident Member of Technical Staff, AT&T Bell Laboratories.
1976 – 1978:Member of Technical Staff, Central Research Laboratories, Varian Associates, Palo Alto, CA.
1975 – 1976:Postdoctoral Fellow, School of Electrical Engineering, Cornell University, Ithaca, NY.

Professional affiliations

Fellow: Institute of Electrical and Electronics Engineers (IEEE)
Fellow: American Association for the Advancement of Science (AAAS)
Fellow (life): American Physical Society (APS)
Member: Material Research Society (MRS), Optical Society of America (OSA), Eta Kappa Nu, Sigma Pi Sigma
Life member: Sigma Xi, Phi Kappa Phi
Listed in Who's Who in the Midwest, American Men and Women in Science, Who's Who in America, Who's Who in Engineering, and International Men of Achievement.

PUBLICATIONS

Some 1000 publications, 33 book chapters, 40 review and popular articles, a two volume book on MODFETs and a book on Nitride Semiconductors and Devices. Ranked 19th among 517,111 physicists in terms of citations and citation impact between 1981 and 1997.

List of five closely related and five other significant publications

1. M. A. Reshchikov, J. Cui, F. Yun, A. Baski, M. I. Nathan, R. Molnar, and Hadis Morkoç, "GaN based quantum dot heterostructures", Spring MRS meeting, April 24-27, 2000, San Francisco.
2. Z-Q. Fang, D. C. Look, C. Lu and H. Morkoç, "Electron and hole traps in GaN p-i-n photodetectors grown by reactive molecular beam epitaxy" Appl. Phys. Lett. In press.

3. K. T. Tsen, C. Koch, Y. Chen, H. Morkoç, J. Li, J. Y. Lin, H-X. Jiang, " Observation of electron Raman scattering from Mg-Doped wurtzite GaN" Applied Physics Letters, vol.76, no.20, pp.2889-2891, 15 May 2000.
4. J. E. Brown, C. Cai, M. I. Nathan, P. Chow, J. M. Van Hove, A. Wowchak, and H. Morkoç, " Bias assisted, room temperature photoelectrochemical (PEC) etching of p-type GaN" Appl. Phys. Letts. In press.
5. Fabio Sacconi, Aldo Di Carlo, P. Lugli, and Hadis Morkoç, "Spontaneous and Piezoelectric polarization effects on the output characteristics of AlGaN/GaN heterojunction Modulation Doped FETs", IEEE Trans on Electron devices, special issue, Eds. J. Zolper and U. K. Mishra, in press.
6. V. Potin, P. Ruterana, G. Nouet, R. C. Pond, H. Morkoç, "Mosaic growth of GaN on (0001) sapphire: A high-resolution electron microscopy and crystallographic study of threading dislocations from low-angle to high-angle grain boundaries", Physical Review B-Condensed Matter, vol.61, no.8, pp.5587-5599,15 Feb. 2000.
7. Roberto Cingolani, A. Botchkarev, H. Tang , Hadis Morkoç, Giuliano Colií and Mauro Lomascolo, A. Di Carlo, and P.Lugli, "Spontaneous polarization and piezoelectric field in $GaN/Al_{0.15}Ga_{0.85}N$ quantum wells: impact on the optical spectra" Phys. Rev. B-Condensed Matter, vol.61, no.4, pp.2711-2715, 15 Jan. 2000.
8. Hadis Morkoç and Roberto Cingolani, and Bernard Gil, "Polarization Effects in Nitride Semiconductor Device Structures, and Performance of Modulation Doped Field Effect Transistors" Solid State Electronics, vol.43, no.10, pp.1909-1927, October 1999.
9. Tomasz J. Ochalski, Bernard Gil, Pierre Lefebvre, Nicolas Grandjean, Mathieu Leroux, Jean Massies, Shuji Nakamura, and Hadis Morkoç, Appl. Phys. Letts. Vol. 74, No. 22, pp. 3353-3355, 1999.
10. B. H. Bairamov, Ö. Gürdal, A. Botchkarev and H. Morkoç, G. Irmer and J. Monecke, "Direct experimental evidence of tensile strain in wurtzite structure n-GaN layers grown on n-Si (111) using AlN buffer", Phys. Rev. B-Condensed Matter, vol.60, no.24, pp.16741-16746, 15 Dec. 1999

C. Recent Collaborators:
Q. Zhu (Brookhaven); J. J. Song (Oklahoma State Univ.), R. Ruterana, A, Haiire, G. Nouet, (Laboratoire d'Etude et de Recherche sur les Materiaux); P. Lefebvre, J. Allègre, B. Gil, A. Kavokin and H. Mathieu (Univ. of Montpelier, France); Y. Ho, K. Y-Tong and Charles Surya (Hong Kong Polytechnique); J. Y. Lin and H. Jiang (Kansas State); R. T. Williams (Wake Forest Univ.); G. Smith, M. Estes, C. W. Litton, D. C. Look. D. Reynolds, P. Hemenger, W. Mitchell, K. Jenkins and L. Kehias (Wright Laboratories); B. Goldenberg, W. Yang, and S. Krishnankutty (Honeywell, Inc.); B. H. Bairamov, R. A. Evarestov, Yu E. Kitaev and E. Jahne (Ioffe Institute, Russia); K. T. Tsen and D.J. Smith (Arizona State); E. Haller and S. Liliental-Weber (Univ. of California and Lawrence Berkeley Laboratory); J. M. Gibson, M. Yeadon, A. Rockett, J. E. Green, L. Allen, D. Cahill and J. White (Univ. of Illinois-Urbana-Champagne), R. Cingolani, (University of Lecce, Italy), D. Smith and K. T. Tsen, (Arizona State); M. Khan (Univ. of Southern Carolina); M. Skowronski (Carnegie Mellon); W. Lambrecht and B. Segall (Case Western).

D. Graduate students sponsored by PI:
T. Lehrer, G. Martin, D-G. Park, J. Reed, Z. Fan, C. Lu, G.B. Gao, G. Popovici, B. Sverdlov, F. Hamdani, A. Salvador, S.N. Mohammad, A. Botchkarev, H. Tang, S. Unlu, J. Chen, T. Strite, and D. Diatzua

E. Graduate advisor: Prof. L. F. Eastman, Cornell University

Synergistic Activities: The PI has established an undergraduate course in advanced concepts in semiconductors. In conjunction with that course, he trained 6 undergraduate courses on aspects of GaN ranging from growth, lithography, fabrication to analysis. He established the first every GaN meeting, was instrumental in establishing other domestic and international meetings in GaN and related materials and devices for the dissemination of information. He wrote status reports on the status and prospects on wide bandgap semiconductors, which were distributed very widely, and played a critical role in the popularity of GaN. He wrote critical review papers, book chapters and a book on the topic. He also presented many seminars at numerous institutions, including many business concerns, across the globe to spread the message. Last but not least, he collaborated with some 20 groups to advance the engineering and science of GaN.

Facilities available in the Virginia Commonwealth University Microelectronics RESEARCH LABORATORY

In 1991, the President of VCU, Dr. Eugene Trani, laid the foundation for establishing the School of Engineering at VCU. Great strides have since been made in that the new 147,000 square foot building was completed in less than two years after ground breaking and occupied in June 1998. The building houses classrooms and offices, and has already received many excellent reviews. The Microelectronics Center, adjacent to the main building, was established under the leadership of Gov. George Allen and local industrial leaders for research and teaching purposes. The Engineering School has programs in Electrical Engineering, Biomedical Engineering, Chemical Engineering and Mechanical Engineering. These programs are interdisciplinary and designed to explore and teach the latest technology in nanoscience and nanotechnology and confluence of physical and biological sciences at the graduate and undergraduate levels.

The micro and nanoelectronics research and education is performed in the Virginia Microelectronics Center (VMC), a 27,000 square foot four-story building. The first floor of the VMERC is devoted to silicon technology and undergraduate education. The necessary equipment is being installed as provided by Motorola, Inc. The sponsored research programs are conducted on the third floor of the VMC, which has approximately 2500 square feet of class 1000 space. Even though the laboratory receives new tools continually, already, an MBE system designed for depositing nitride semiconductors has been installed and calibrated. The SVT Reactive MBE system is also equipped with an RF nitrogen source for maximum flexibility. In addition, the workhorse, perhaps the most well known MBE system in the world that the group of Prof. Morkoç has used since 1979, is producing device quality layers. This Riber 1000 MBE system has been converted to reactive MBE system. On the deposition side again, a custom MOCVD system designed for semiconductor nitrides is being installed. This custom MOCVD system has a gas manifold and deposition reactor, which was manufactured by EMCORE Corporation and SVT Associates, respectively. The system gives the group the added flexibility and advantage for nitride research. It has tremendous latitude in terms of gas delivery and eliminates much of the interdependence among the parameters that often hampers conventional MOCVD systems. The group also was fortunate to have received a third MBE system as a gift from Bell Laboratories, Lucent Technologies. On the fabrication side, the research laboratory is equipped with photo and electron beam lithography systems and metallization and etching facilities. The LEO 440 microscope has a 2 nm resolution in the imaging mode and is layered with a Nabity pattern generation system. The research oriented RF dry etching system was designed in the plasma group at Wright Patterson Air Force Research Laboratory. This system is designed for convenience and low damage and easily configurable for plasma diagnosis for an easy correlation of plasma parameters to etching characteristics.

Recently, we have added a Philips X'pert MRD high resolution X-ray diffraction system. X-ray diffraction (XRD) is a versatile analytical technique used in our research to analyze structural properties of crystalline materials. At VCU the system will be used for high resolution applications – such as rocking curves of heteroepitaxial layers; diffraction space maps of thick heteroepitaxial structures and partially relaxed structures; reflectivity measurements of layer thickness, interface/sample quality and density, and structural properties of nanostructures. The X'Pert - MPD system utilizes specially developed PREFIX (pre-aligned, fast interchangeable) optical modules which enable you to switch from application to application by simply swapping the optical module. Dedicated analytical instrument performance is ensured due to the wear-free reference surfaces on the PREFIX modules. The MRD cradle provides the versatility of an open Eulerian cradle, an x-y stage and z translation to accommodate applications needing utmost accuracy.

Another new tool that was added to our arsenal of tools is a KLA Tencor Alpha Stepper 500 surface prolifometer. This is a very versatile system for precise measurement of very thin step heights on wafers and small samples. Flexible software allows analysis of up to 39 surface parameters with simultaneous display. Moreover, we added a Digital Instruments Nanoscope III multimode AFM with STM capability, which is pivotal in characterization Q dots, layer growth even extended defects and charge states.

The deposition and fabrication laboratories enjoy conveniently delivered utilities such as gaseous and liquid nitrogen, process vacuum, compressed dry air, process cooling water, DI water, scrubbed and regular exhausts, and much more. The air-flow system for class 1000 is designed to diffuse the air in a way to be extremely quiet. This combined with all the roughing pumps and compressors being located in service bays lend to a very comfortable and environmentally friendly laboratory space in which to work. Moreover, the group has electrical and optical characterization laboratories giving the researcher full access to a full range of equipment to carry out research without leaving the laboratory. The group has a long term working relationship with many specialists across the country and abroad for research requiring expertise and training not available on site.

Lastly, a good deal of optical characterization facilities exists which allow PL, absorption and reflectance measurements in semiconductor nitrides. We recently added a Ti-Sapphire laser with SHG and THG, and picosecond temporal capabilities. We are in the process of installing a Lake Shore 7504 automated Hall measurement system. The sponsored research programs will be conducted in the third floor of the VMC with approximately 2500 square feet of class 1000 space whose diagram is shown in **Fig. 1,** and fourth floor where the optical measurement laboratories are located.

For details of our present facilities and images, please visit our web site

http://www.vcu.edu/egrweb/vmc/research/index.html

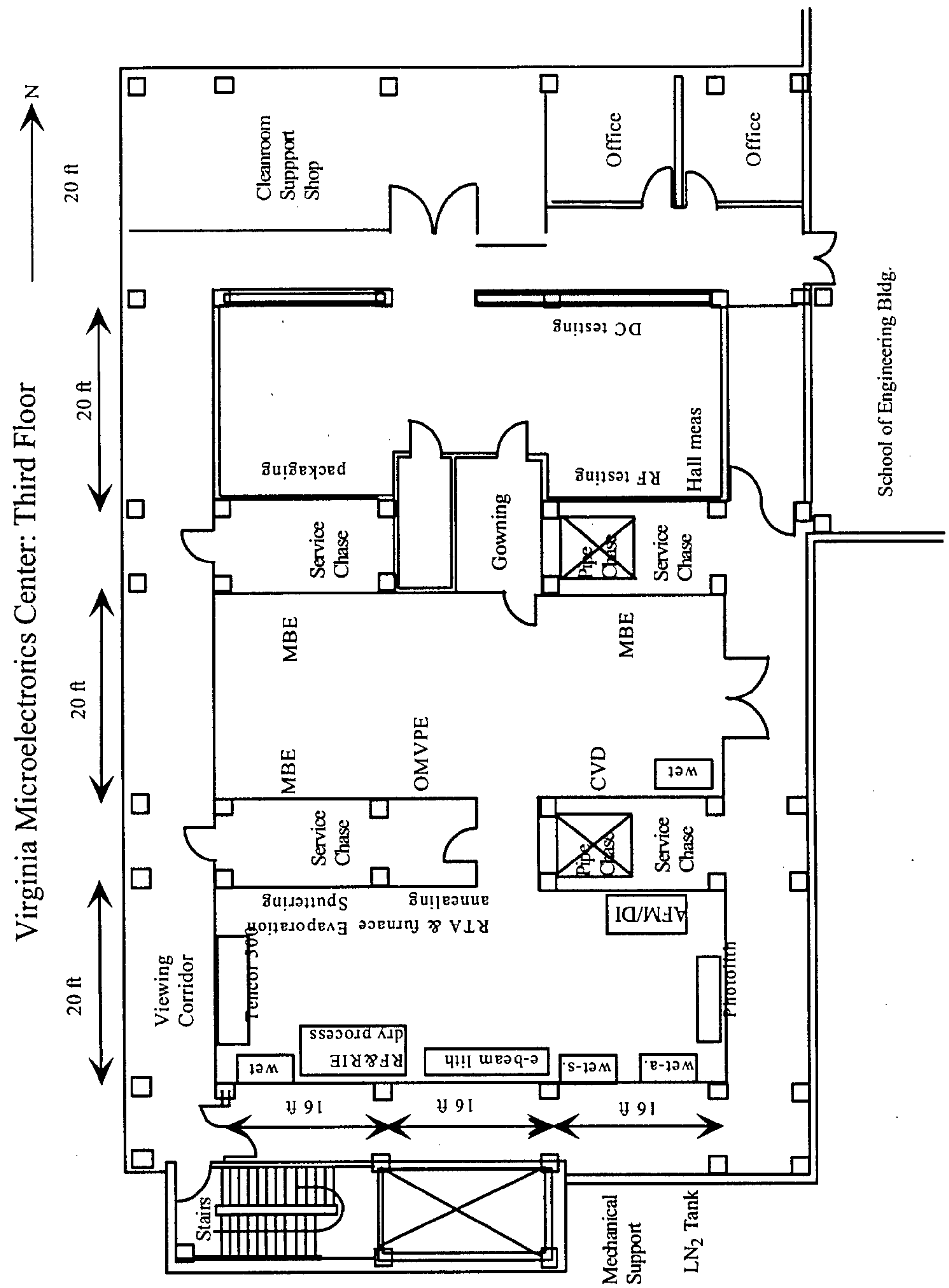

Fig. 1. Layout of the research present equipment and clean room in the Virginia Microelectronics Center. Layout of the research present equipment and clean room in the Virginia Microelectronics Center.