

High-Field Quantum Transport in Nanostructured Devices and Integrated Circuits

Professor Dr. Vijay K. Arora

Final Report

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The Research Management Center
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PROJECT OUTCOMES SUMMARY

The application of quantum waves as carriers of information was investigated in a number of activities involving FKE staff, Ph. D. scholars, and PSM students (all named as members of the effective teams in the papers listed below). As outlined in the project design, the project activities transferred technical know-how to staff and students of UTM working in cross-disciplinary teams. It was a splendid display of innovations through teamwork in the true spirit of the Principle of Complementarities, each team player doing what was best for him. The investigations resulted in 5 journal papers with 6 papers in the pipeline being reviewed for possible publication and more to follow. The paper in the *Applied Physics Letters* was given Premium Award for the most outstanding paper with the highest impact factor at the Majlis Anugerah *Citra Karisma* held on May 15, 2008, Dewan Sultan Iskandar, UTM. A number of papers were published in conference proceedings. The knowledge obtained was disseminated through seminars and professional talks under the IEEE Distinguished Lectures Program and also at regional and international conferences. The project outcome is showing its impact on the international scientific community, on students through mentoring program on research-based education, on the FKE that is considering nanotechnology as one of its strengths, and on UTM reputation through its international visibility that may allow it to be viewed as a global educational entity. Every stakeholder benefited from the proposed activity with win-win paradigm for all. FKE, the seat of project execution, is founded on a no-walls culture of openness, promoting collaboration and discovery across disciplines and institutions, as well as across communities, cultures and continents. This allowed us to build bridges and open doors for research and innovations that inshaAllah will continue for years to come. Curiosity through research interplaying with reason gives us science; science interplaying with necessity gives us technology. The interaction of science and technology is what helps bring about understanding of the world, connecting with the world, thereby contributing to the transformation of the world. By integrating curiosity, reason and necessity, UTM will play its part, hopefully a big part, in the global knowledge community,

dedicated to transforming our world into a better place. I, as principal investigator, thank all those involved in the project and all those who provided invaluable help to sail through the complex maze of the UTM system. All have been duly acknowledged at the end of this report.

PAPERS PUBLISHED—INTERNATIONAL JOURNALS

Vijay K. Arora, Michael L. P. Tan, Ismail Saad, and Razali Ismail, “Ballistic quantum transport in a nanoscale metal-oxide-semiconductor field effect transistor,” *Applied Physics Letters*, Volume 91, 103510 (2007). Award winning paper at UTM Citra Karisma ceremony on May 15, 2008.

Michael L. P. Tan, Ismail Saad, Razali Ismail, and Vijay K. Arora, “Enhancement in nano-RC switching delay due to the resistance blow-up in InGaAs,” *NANO*, Volume 2, No. 4, pp. 233-237 (2007).

Mohammad Taghi Ahmadi, Hui Houg Lau, Razali Ismail, and Vijay K. Arora, “Current-Voltage Characteristics of a Silicon Nanowire Transistor,” *Microelectronics Journal*, in press.

Ismail Saad, Michael L. P. Tan, Aaron Chii Enn Lee, Razali Ismail, and Vijay K. Arora, “Scattering-Limited and Ballistic Transport in a Nano-CMOS Circuit,” *Microelectronics Journal*, in press.

Ismail Saad, Michael L.P Tan, Ing Hui Hii , Razali Ismail, and Vijay K. Arora, “Ballistic Mobility and Saturation Velocity in Low-Dimensional Nanostructure,” *Microelectronics Journal*, in press.

PAPERS UNDER REVIEW

Mohammad Taghi Ahmadi, Michael L. P. Tan, Razali Ismail, and Vijay K. Arora, “The High-Field Drift Velocity in Degenerately-Doped Silicon Nanowires,” under review for the *International Journal of Nanotechnology*.

Vijay K. Arora and Michael L. P. Tan, “The Circuit Design Beyond Ohm’s Law,” under review for the *IEEE Transactions on Circuits and Systems-Part II: Express Briefs*.

Vijay K. Arora, Michael L. P. Tan, Ismail Saad, Mohammed Taghi Ahmadi and Razali Ismail, “The Dependence of Saturation Velocity on Temperature, Inversion Charge and Electric Field in a Nanoscale MOSFET” under review for the *IEEE Transactions on Electron Devices*.

Mohammad Taghi Ahmadi, Razali Ismail, Vijay K. Arora “The Ultimate Drift Velocity in Carbon Nanotube Field Effect Transistor,” under review for the *Journal of Nanomaterials*.

Ismail Saad, Michael L. P. Tan, Razali Ismail, Vijay K. Arora, “Nano-Physics of Transient Phenomenon in Semiconducting Devices and Circuits,” under review for the *Journal of Solid State Science and Technology*.

Ismail Saad, Razali Ismail and Vijay K. Arora, “Investigation on the effects of oblique rotating ion implantation (ORI) for nanoscale vertical MOSFET”, under review for the *Journal of Solid State Science and Technology*.

PAPERS PRESENTED/PUBLISHED AT CONFERENCES/PROCEEDINGS

Ismail Saad, Michael L. P. Tan, Razali Ismail, Vijay K. Arora, “Nano-Physics of Transient Phenomenon in Semiconducting Devices and Circuits” *Program and Abstract Book of the Regional conference on Solid State Science and Technology*, November 27-29, 2007. To be published in the *Journal of Solid State Science and Technology*.

Ismail Saad, Razali Ismail and Vijay K. Arora, “Investigation on the effects of oblique rotating ion implantation (ORI) for nanoscale vertical MOSFET”, *Program and Abstract Book of the Regional conference on Solid State Science and Technology*, November 27-29, 2007. To be published in the *Journal of Solid State Science and Technology*.

Vijay K. Arora, “New Insights on Ballistic versus Scattering-Limited Transport in a Nanoscale Metal-Oxide-Semiconductor-Field-Effect-Transistor,” keynote invited paper, pp. A1-A11, *Proceedings of the Regional Symposium on Microelectronics 2007 (RSM2007)*, Penang, Malaysia, December 3-6, 2007, IEEE Press, New York (2007).

Aaron Chii Enn Lee, Hui Houg Lau, Ing Hui Hii, and Vijay K. Arora “The Drift Response to the Applied Electric field in an InGaAs Quantum-Well Nanostructure,” pp. 574-579, *Proceedings of the Regional Symposium on Microelectronics 2007 (RSM2007)*, Penang, Malaysia, December 3-6, 2007, IEEE Press, New York (2007).

M.Taghi Ahmadi, Ismail Saad, Michael L.P.Tan, Razali Ismail, and Vijay K. Arora “The Ultimate Drift Velocity in Degenerately-Doped Silicon,” pp. 569-573, *Proceedings of the Regional Symposium on Microelectronics 2007 (RSM2007)*, Penang, Malaysia, December 3-6, 2007,

Ismail Saad, Ing Hui Hii, Aaron Chii Enn Lee, Hui Houg Lau, Razali Ismail and Vijay K. Arora “The Circuit Design Beyond Ohm’s Law: Applications To Series, Parallel, And CMOS Configurations,” pp. 65-70, *Proceedings of the Regional Symposium on Microelectronics 2007 (RSM2007)*, Penang, Malaysia, December 3-6, 2007, IEEE Press, New York (2007).

Vijay K. Arora, “Ballistic Quantum Transport in Nano Devices and Circuits,” invited paper, *Proceedings of the IEEE International Nanoelectronics Conference (NEC2008)* 24 -27 March 2008, Shanghai, China. The paper is also available in IEEE Xplore.

Hui Houg Lau, Ing Hui Hii, Aaron Chii Enn Lee, M.Taghi Ahmadi, Razali Ismail, and Vijay K. Arora “The High-Field Drift Velocity in Degenerately-Doped Nanowires,” invited paper, *Proceedings of the IEEE International Nanoelectronics Conference (NEC2008)* 24 -27 March 2008, Shanghai, China. The paper is also available in IEEE Xplore and has been invited for publication in the International Journal of Nanotechnology.

Mohammad Taghi Ahmadi, Ismail Saad, Razali Ismail, and Vijay K. Arora “The Ultimate Drift Velocity in Degenerately-Doped Nanowire,” pp. 357-358, *Proceedings of the 2nd Conference on Nanostructures*, March 11-14, 2008, NS2008, Kish Island, Iran, edited by A. Simchi, copyrighted by the Institute of Nanoscience and Nanotechnology, Sharif University of Technology, Tehran, Iran.

Ismail Saad, Mohammad Taghi Ahmadi, Razali Ismail, and Vijay K. Arora “High-Field Drift Velocity Limitation in Quasi-2D Nanostructures (1D Quantum Limit),” pp. 412-413, *Proceedings of the 2nd Conference on Nanostructures*, March 11-14, 2008, NS2008, Kish Island, Iran, edited by A. Simchi, copyrighted by the Institute of Nanoscience and Nanotechnology, Sharif University of Technology, Tehran, Iran.

Ismail Saad, Michael L. P. Tan, Razali Ismail, Vijay K. Arora, “Nano-Physics of Transient Phenomenon in Semiconducting Devices and Circuits” *Program of the Regional conference on Solid State Science and Technology*, November 27-November 29, 2007, Johor Bahru, Malaysia, To be published in the Journal of Solid State Science and Technology.

Mohammad Taghi Ahmadi, Hui Houg Lau, Razali Ismail, and Vijay K. Arora, “Current-Voltage Characteristics of a Silicon Nanowire Transistor,” *Program and Abstract Book of the International Workshop on Recent Advances of Low Dimensional Structures and Devices*, 7-9 April, The University of Nottingham, U. K. The paper is also accepted for publication in the *Microelectronics Journal*.

Ismail Saad, Michael L.P Tan, Aaron Chii Enn Lee, Razali Ismail, and Vijay K. Arora, “Scattering-Limited and Ballistic Transport in a Nano-CMOS Circuit,” *Program and Abstract Book of the International Workshop on Recent Advances of Low Dimensional Structures and Devices*, 7-9 April, The University of Nottingham, U. K. The paper is also accepted for publication in the *Microelectronics Journal*.

Ismail Saad, Michael L.P Tan, Ing Hui Hii, Razali Ismail, and Vijay K. Arora, “Ballistic Mobility and Saturation Velocity in Low-Dimensional Nanostructure,” *Program and Abstract Book of the International Workshop on Recent Advances of Low Dimensional Structures and Devices*, 7-9 April, The University of Nottingham, U. K. The paper is also accepted for publication in the *Microelectronics Journal*.

Vijay K. Arora, invited keynote paper, “Physics Beyond Ohm’s Law Its Impact on Nano-Engineering of Circuits and Systems,” *Program and Abstract Book of the Regional Annual Fundamental Sciences Seminar (RAFSS2008)*, May 27-29, 2008, Ibnu Sina Institute of Fundamental Sciences, UTM.

Mohammad Taghi Ahmadi, Ismail Saad, Razali Ismail, Vijay K. Arora, “Numerical study of Carrier Statistic in Nanostructure Devices,” *Program and Abstract Book of the Regional Annual Fundamental Sciences Seminar (RAFSS2008)*, May 27-29, 2008, Ibnu Sina Institute of Fundamental Sciences, UTM.

Mohammad Taghi Ahmadi, Ismail Saad, Razali Ismail, Vijay K. Arora, “Analytical Study of Drift Velocity in Low Dimensional Devices,” *Program and Abstract Book of the Regional Annual Fundamental Sciences Seminar (RAFSS2008)*, May 27-29, 2008, Ibnu Sina Institute of Fundamental Sciences, UTM.

Vijay K. Arora, “Engineering the Soul of Management in the Nano Era,” *Proceedings of the Portland International Conference on Management of Engineering and Technology 2008 (PICMET2008)*, July 27-July 31, 2008, Cape Town, South Africa. The paper is found at PICMET www.picmet.org, website <http://www.picmet.org/db/finalPDF/08A0123.pdf>.

INVITED SEMINARS/LECTURES

June 22, 2007. IEEE distinguished lecture on “Performance Evaluation of Nano Circuits and Systems with Ballistic Carriers,” Institute of Material Research and Engineering (IMRE), Singapore.

July 25, 2007. IEEE distinguished lecture entitled, “Physics-Based Models for Performance Evaluation of a Nanoscale MOSFET,” Workshop and IEEE Mini-Colloquim in Nano-CMOS, Nanyang Technological University, Singapore.

August 24, 2007. IEEE distinguished lecture entitled, “Human Power Development in Nano-Engineering: Malaysia and World Perspective,” Universiti Malaysia Perlis (UniMAP).

November 2, 2007. Invited talk on “Engineering the Soul of Management by Discovering a Quality Person in You,” Kurukshetra University, Kurukshetra, India.

November 5, 2007. IEEE distinguished lecture on “Failure of Ohm’s Law: Its Implications on Design of Nanoelectronic Devices and Circuits,” Delhi University, India.

November 20-21, 2007. Invited Workshop speaker and facilitator on “Outcome-Based Education: Planning and Delivery,” Outcome-Based Workshop, Equatorial Hotel, Kuala Lumpur.

November 22, 2007. “Human Power Development in Nano-Engineering: Malaysia and World Perspective,” Telekom Malaysia R&D Center, Kuala Lumpur.

March 20, 2008. IEEE distinguished lecture entitled, "Scattering-Limited and Ballistic Transport in Nano-CMOS," at the Institute of Electronics of the Chinese Academy of Sciences and the Department of Microelectronics at Peking University, organized by Chinese Academy of Sciences and IEEE-EDS Chapter in Beijing.

March 23, 2008. IEEE distinguished lecture at the 15th Mini-Colloquim WIMNACT-15 on Nano-CMOS, where 5 DLs presented their work at the Shanghai Institute of Microelectronics.

March 28, 2008. Gave an IEEE distinguished talk at the 15th Mini-Colloquim WIMNACT-15 on Nano-CMOS, where 5 DLs presented their work at Zhe-Ziang University in Hangzhou.

PROFESSIONAL VISITS TO OTHER RESEARCH CENTERS

June 21-22, 2007. Visited National University of Singapore (June 22) and Nanyang Technological University (June 21) to assess their facilities in Nano-Engineering for possible collaboration in Nano-Engineering.

November 22-23, 2007. Visited Telekom Malaysia R&D Center and Institute of Microelectronic Engineering and Nanotechnology, University Kebangsaan Malaysia (UKM) .

PROFESSIONAL SERVICE THROUGH KNOWLEDGE ENGAGEMENT

August 16, 2007. Reviewed a paper entitled "Tailoring the Carrier Mobility of Semiconductor Nanowires by Remote Dielectrics" by Aniruddha Konar and Debdeep Jena , Notre Dame University, for possible publication in Applied Physics Letters.

August 30, 2007. Reviewed a paper on “An Image Processing Approach Towards Classification of Defects on printed Circuit Board,” by Noor Khafifah Khalid and Zuwairie Ibrahim, UTM, for possible publication in *Elektrika*.

September 17, 2007. Reviewed a paper on “Integration of Sustainability and Industrial Mentors into Capstone Design,” Kimberly Ogden and Paul Blowers, University of Arizona Department of Chemical and Environmental Engineering, Tucson, Arizona USA 85721, for publication in conference *Proceedings of the International Conference on Engineering Education and Research* (Theme: Innovations in Information and Communication Technologies), 02-07 December, 2007, Melbourne, Australia.

September 17, 2007. Reviewed a paper entitled “Blending Best Practice: The New Approach to Chemical Engineering at Manchester,” Esther Ventura-Medina*, Edward P.L. Roberts, Leo Lue, Arthur Garforth, School of Chemical Engineering and Analytical Science. The University of Manchester. PO Box 88, Sackville St, Manchester, M60 1QD, United Kingdom, for publication in conference *Proceedings of the International Conference on Engineering Education and Research* (Theme: Innovations in Information and Communication Technologies), 02-07 December, 2007, Melbourne, Australia.

October 24, 2007. Reviewed a paper entitled “High-field transport in semiconductor superlattices for interacting Wannier-Stark levels,” by Angelo Guida, Lino Reggiani, and Marcello Rosini, Università del Salento, Via Arnesano s/n, 73100 Lecce, Italy for publication in the *Physical Review*.

December 6, 2007. Reviewed a paper entitled “Process and Characterization of 50 nm vertical double gate MOSFET (VDGM) with FILOX using TCAD tools” by Ismail Saad and Razali Ismail, Universiti Teknologi Malaysia, for publication in *Jurnal Fizik Malaysia*.

December 9, 2007. Reviewed a paper entitled, “Xt–Xl valley crossover and deformation potential in AlP-GaP quantum wells,” by M.P. Semtsiv, O. Bierwagen, and W.T. Masselink Department of Physics, Humboldt University Berlin, Newtonstrasse 15, D-12489 Berlin, Germany and M. Goiran, J. Galibert, and J. L’etoin Laboratoire National des Champs Magnetiques Pulsés, 143 avenue de Rangueil, 31400 Toulouse Cedex 4, France, for publication in the *Physical Review*.

December 12, 2007. Reviewed a paper entitled "Electrical Characterization of CeO₂/Si Interface Properties of Metal-Oxide-Semiconductor Field-Effect Transistors with CeO₂ Gate Dielectric" by Chun-heng Chen, Ingram Yin-Ku Chang, Fu-Chien Chiu, and Joseph Lee, National Tsing-Hua University, for possible publication in the *Applied Physics Letters*.

February 3, 2008. Reviewed a paper entitled, “Self-sustained spin-polarized current oscillations in multiple quantum well structures,” by R. Escobedo, M. Carretero, L.L. Bonilla, G. Platero, Universidad de Cantabria, Santander, Spain for possible publication in the *Physical Review*. Also, the dispute among the reviewers was adjudicated and confidential recommendations made.

March 4, 2008. Reviewed a paper entitled, "Electrical transport properties in indium tin oxide films prepared by electron-beam evaporation," by Xin-Dian Liu, Enyong Jiang, and De Xian Zhang, Tianjin University, China, for publication in the *Journal of Applied Physics*.

March 4, 2008. Reviewed a paper entitled “FinFET reliability study by forward gated-diode R–G current method,” by Chenyue Ma, Bo Li, Lining Zhang, Feng Liu, Jin He, and Xing Zhang, Institute of Microelectronics, EECS, Peking University, Beijing 100871, P. R. China for publication in the *Applied Physics Letters*.

April 28, 2008. Reviewed a paper entitled, “Absorptive Optical Bistability In Hybrid Laser Structure,” by Pukhraj Vaya, Department of Electronics and Communication, Amrita School of Engineering, Bangalore, India and Tan Chee Leong, Optoelectronic Lab, School of Photon Science and Technology, Gwangju Institute of Science and Technology, Korea for publication in *Research Letters on Optics* journal.

June 23, 2008. Reviewed a paper entitled, “Context Based Medical Image Compression for Ultrasound Images with Contextual Set Partitioning in Hierarchical Trees Algorithm,” by M.A. Ansari and R.S. Anand, Indian Institute of Technology, Roorkee, for possible publication in *Advances in Engineering Software*.

ACKNOWLEDGMENTS

My heartfelt gratitude for the wonderful UTM hospitality goes to Professor Dr. Siti Hamisah, Deputy Vice-Chancellor, Academics and Internationalization. I feel welcome member of the UTM community with her constant monitoring that I am comfortably placed. My wife Rashmi joins me in giving our earnest commendation for her leadership in the true spirit of *valuing people* that many administrators talk about but find hard to deliver. Without her welcome in UTM environment and respect for talents no matter where these come from, the quality delivery of publishable results and human development services were not possible. I am taking many fond memories of my UTM stay as I leave for my permanent assignment. I am on stand by in providing any support that UTM may need in years to come as it discovers internationalization in order to be a Global Discovery University.

Dato’ Dean Professor Dr. Ahmad bin Darus is a magnificent person well liked by his subjects in the FKE. He was always around the corner to make sure that I am comfortably placed in his Deandom. I can assure him that everyone in the FKE has been very respectful of my stay here and accorded help when and where needed. Complementing the Deandom also includes both deputy deans Prof. Dr. Abdul Halim and Professor Shamsudin. Professor Halim shared the platform with me on outcome-based education in Kuala Lumpur as well as in UTM. I can assure him that the lessons learned also apply to research and have been implemented in executing this project. Professor Shamsudin have been a wonderful guide and companion on research matters. I am confident it was because of him that the UTM was able to award highest honor for publication in an international journal. We had a wonderful discussion on plagiarism and report writing. Dr. Ooi Chia Yee and Mr. Lim Cheng Siong have been wonderful neighbors and friends during the execution of this project, spending time on policies and procedures and desired translations from Bahasa to English not only in FKE, but also for communications outside the UTM, even accompanying on several occasions to the centers where work needed to be done. Ms. Rodhiah Bt Ahmad, Personal Assistant to Dean, has been very supportive in looking after all the work that has to be completed through the dean’s office.

Ms. Maimunah Salleh, Assistant Registrar FKE deserves a special word of gratitude for looking after my transition from the U. S. to Malaysia and back. She is the one who personally walked through the UTM labyrinth for getting my bonuses, travel tickets, to name

a few, in the true spirit of Human Resources Management. Maimunah, we (me and my wife Rashmi) adore your timely and much needed help. We assure you that this help added tremendous value to our productivity and in our ability to develop human resources in the UTM system.

In managing project of this size with meager resources, the support of so many co-workers is indeed very valuable. First and foremost in the list of co-workers and colleagues, I thank Professor Dr. Ruzairi bin Hj. Abdul Rahim without whose support it was impossible to receive this grant. He carefully ran the proposal through the UTM network and was informing me constantly the development stage of the proposal. Even though the grant was awarded 3-4 months later than its proposed starting date of July 1, 2007, the project advanced smoothly right from its inception on his assurances that approval will come. Professor Razali bin Ismail has been a wonderful host and partner in the project in managing resources and providing help when and where needed. Dr. Manaf is to be thanked for initiating seminar series and being the founding Director of the Center for Material Innovations and Nanoelectronics (MINE) within the FKE. I am happy to be part of the Center in its formative stages. I hope the Center becomes *mine* of information in nano-engineering that everyone in the Center is proud to say: "mine to own," in the true spirit of being a stakeholder.

A teacher is not a teacher unless there are dedicated willing students to learn from his presence and support his efforts for advancement of knowledge and do whatever is needed to succeed in life. My PSM students, Ing Hui Hii, Aaron Chii Enn Lee, Hui Houg Lau have been around to carry out research of the caliber of what graduate students perform. Ph. D. scholars Mr. Ismail Saad and Mohammad Taghi Ahmadi have provided wonderful support in preparing manuscripts and drawings to speed up the publication process. I wish I could have given more attention to their needs. Ismail was always there to take me to RMC to process request for conferences and supplies, performing the job of a research officer without any pay or credit. He deserves a special word of admiration for providing this service that normally goes thankless.

I leave final words of accolade for Michael L. P. Tan, not that I consider him the least important, rather because I consider him the most important to maintain my lifeline in the jumble of UTM and Malaysian system. My association with him runs much deeper than this one year period. I have known him since December 2004 when he was tutor pursuing his M. S. degree. He has been constantly teasing my mind power (information processing capability of brain) by asking insightful questions. He was instrumental in my settling in the UTM environments constantly reminding me of my appointments and assignments. I missed him a lot when he boarded plane for his higher studies at the University of Cambridge and still miss him as I leave UTM for my natural habitat at Wilkes University. Michael, I found a true friend in you and I wish you will return to your country with the laurels, success, and glory for which you left your dear country with a hope to bring value to UTM and beyond. UTM needs scholars like you who can make difference in the life of others. Please stay connected.

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