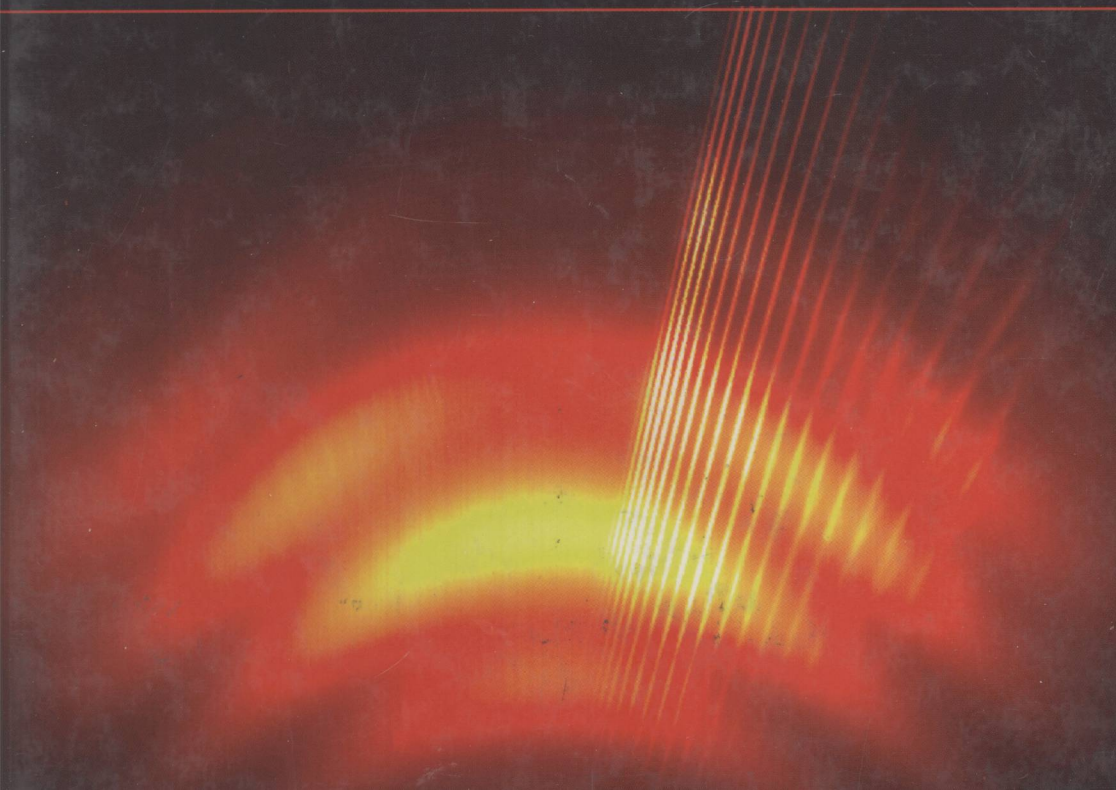
Future Trends in Microelectronics

Up the Nano Creek

Serge Luryi, Jimmy Xu, and Alex Zaslavsky



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Preface

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This book is a brainchild of the fifth workshop in the *Future Trends in Microelectronics* series (FTM-5). The first of the FTM conferences, "*Reflections on the Road to Nanotechnology*", had gathered in 1995 on Ile de Bendor, a beautiful little French Mediterranean island.[1] The second FTM, "*Off the Beaten Path*", took place in 1998 on a larger island in the same area, Ile des Embiez.[2] Instead of going to a still larger island, the third FTM, "*The Nano Millennium*" went back to its origins on Ile de Bendor in 2001.[3] To compensate, the next FTM, "*The Nano, the Giga, the Ultra, and the Bio*" took place on the biggest French Mediterranean island of them all, Corsica.[4] Normally, the FTM workshops gather every three years; however, the FTM-4 was held one year ahead of the usual schedule, in the summer of 2003, as a one-time exception. Keeping in line with its inexorable motion eastward, the latest FTM workshop, "*Up the Nano Creek*", had convened on Crete, Greece, in June of 2006.

The FTM workshops are relatively small gatherings (less than 100 people) by invitation only. If you, the reader, wish to be invited, please consider following a few simple steps outlined on the conference website. The FTM website at *www.ece.sunysb.edu/~serge/FTM.html* contains links to all past and planned workshops in the series, their programs, publications, sponsors, and participants. Our attendees have been an illustrious lot. Suffice it to say that among FTM participants we find five Nobel laureates (Zhores Alferov, Herbert Kroemer, Horst Stormer, Klaus von Klitzing, and Harold Kroto) and countless others poised for a similar distinction. To be sure, high distinction is not a prerequisite for being invited to FTM, but the ability and desire to bring fresh ideas is. All participants of FTM-5 can be considered authors of this book, which in this sense is a collective treatise.

The main purpose of FTM workshops is to provide a forum for a free-spirited exchange of views among the leading professionals in industry, academia, and government. It is a common view among the leading professionals in micro-electronics, that its current explosive development will likely lead to profound

paradigm shifts in the near future. Identifying the plausible scenarios for the future evolution of microelectronics presents a tremendous opportunity for constructive action today.

For better or worse our civilization is destined to be based on electronics. Ever since the invention of the transistor and especially after the advent of integrated circuits, semiconductor devices have kept expanding their role in our lives. Electronic circuits entertain us and keep track of our money, they fight our wars and decipher the secret codes of life, and one day, perhaps, they will relieve us from the burden of thinking and making responsible decisions. Inasmuch as that day has not yet arrived, we have to fend for ourselves. The key to success is to have a clear vision of where we are heading.

Some degree of stability is of importance in these turbulent times and should be welcome. Thus, although the very term "*microelectronics*" has been generally re-christened "*nanoelectronics*", we have stuck to the original title of FTM workshop series.

The present volume contains a number of original papers, some of which were presented at FTM-5 in oral sessions, other as posters. From the point of view of the program committee, there is no difference between these types of contributions in weight or importance. There was, however, a difference in style and focus – and that was intentionally imposed by the organizers. All speakers were asked to focus on the presenter's views and projections of future directions, assessments or critiques of important new ideas/approaches, and *not* on their own achievements. This latter point is perhaps the most innovative and distinguishing feature of FTM workshops. Indeed, we are asking scientists not to speak of their own work! This has proven to be successful, however, in eliciting powerful and frank exchange. The presenters were asked to be provocative and/or inspiring. Latest advances made and results obtained by the participants could be presented in the form of posters and group discussions.

Each day of the workshop was concluded by an evening panel or poster session that attempted to further the debates on selected controversial issues connected to the theme of the day. Each such session was chaired by a moderator who invited two or three attendees of his or her choice to lead with a position statement, with all other attendees serving as panelists. The debate was forcefully moderated and irrelevant digressions cut off without mercy. Moderators were also assigned the hopeless task of forging a consensus on critical issues.

All FTM workshops adhered to these principles in the past and, hopefully, will do so in the future. To accommodate these principles, the FTM takes a format that is less rigid than usual workshops to allow and encourage uninhibited exchanges and sometimes confrontations of different views. A central theme is designed together with the speakers for each day. By the tradition of FTM, the first day belongs to "*Captains of Industry*" who set the themes for the day, culminating with the "*Captains' Roundtable*" panel in the evening. At FTM-5 this panel was called "*Prospecting Up the Nano Creek*".

Another traditional feature of FTM workshops is a highly informal vote by the participants on the relative importance of various fashionable current topics in

modern electronics research. This tradition owes its origin to Horst Stormer, who composed the original set of questions and maintained the results over four conferences. These votes are perhaps too bold and irreverent for general publication, but they are carefully maintained and made available to every new generation of FTM participants. Unfortunately, Horst missed the Crete gathering, but the tradition was maintained in his absence. Perhaps, one day we shall convince him to edit these votes and open them to general public. Another traditional vote concerned the best poster. The 2006 winning poster was "Formation of three-dimensional SiGe quantum dot crystals" by Detlev Grützmacher.

From all the deliberations and discussion at FTM-5 the following trends could be discerned, with the caveat that our crystal ball is as muddy as ever.

Firstly, although silicon is undoubtedly still full of steam, the word "post-CMOS" has become a commonplace. Somehow, the general perception by FTM attendees of CMOS Technology Roadmap predictions went from "*will be fulfilled ahead of schedule*" to "*should not be taken too seriously*", in a very short time.

A clearly discernible trend is the quest for novel and exotic materials. It looks like we are back to fundamentals. The big-brother silicon is clearly pressed (at least in terms of the conference publicity) by its much nimbler sibling carbon, who is capable of self-organizing into nanotubes and buckyballs, not to speak of graphene sheets. Ah well, it is all in column IV. One of the inventors of C_{60}, the Nobelist Harold Kroto, gave an inspiring lecture on Crete, titled "Architecture in nanospace".

Not every contribution presented at FTM-5 has made it into this book (not for the lack of persistence by the editors). Besides the paper version of Kroto's talk, we sorely miss the exciting contributions by Federico Capasso and Cees Dekker. Abstracts of these and all other presentations can be found on the workshop program webpage, *http://www.ee.sunysb.edu/~serge/ARW-5/program.html*

Besides the technical sessions and voting on the future trends, the FTM-5 program had room for events of general culture. Harold Kroto gave a passionate lecture, defending the Age of Reason, which in his view is under serious attack. Dr. Anna Zdanovich delivered a delightful lecture on the "Mystical symbolic language of byzantine icons". These were very well-received digressions and we intend to continue such practices at FTM as another trend of the future.

The FTM meetings are known for the professional critiques – or even demolitions – of fashionable trends, that some may characterize as hype. The previous workshops had witnessed powerful assaults on quantum computing, molecular electronics, and spintronics. The majority of FTM participants did not consider quantum computing a realistic future technology, but gave it credit as an interesting playground for physicists with some hope of settling old debates about the wavefunction collapse and other fundamental issues. It seems that by now most of the hype associated with quantum computing has dissipated and perhaps we can take some credit for the more balanced outlook that has emerged since. The assault continued at FTM-5 where the very concept of fault-tolerant computing was put in question, on theoretical grounds (Dyakonov). Of course,

this is not an issue to be resolved by a vote and both points of view on quantum computing are presented in this book.

We have grouped all contribution into four parts, titled very generally *Physics, Biology, Electronics,* and *Photonics.* The breakdown could not be uniquely defined, because some papers fit all four categories! The discussion of quantum computing, spintronics, molecular electronics and quantum wires went into Part I (*Physics*). The list of controversial papers in Part I includes discussions of "perfect lensing" in negative refraction materials (Efros) and the foundations of laser theory (Spivak and Luryi).

Part II (*Biology*) is first in FTM workshop treatises. Of course, we had talks related to biology and medicine at the previous meetings, but they never comprised a critical mass. One of the papers is entirely biological and contributed by a biologist (Wimmer). This, however, should not scare the physics/electronics/photonics reader, because Eckard Wimmer made it entirely understandable to a layman. Indeed, let us take a random quote from his paper: "UUAAAACAGCUCUGGGGUUGUACCCACCCCAGAGGCCCACGUGG ..." As will become clear from the paper itself, the fact it is so understandable constitutes a grave danger to this world! This is not the only biological danger described in Part II, as we are at least equally scared by micro-array brain implants (Nurmikko).

Parts III (*Electronics*) and IV (*Photonics*) are less dangerous but no less important. In *Electronics* we learn, perhaps with some dismay, how nano-manufacturing is making money, nano-dollar by nano-dollar. We find, perhaps with some sense of *deja vu*, that lithography is again at the cross-roads and that solutions may come from carbon nanotubes. The *Photonics* part will declare terahertz a form of light, even though it was only recently an ultrafast electronic oscillation. This is what happens when one merges nano with nano ...

To produce a coherent collective treatise out of all of this, the interaction between FTM participants had begun well before their gathering at the workshop. All the proposed presentations were posted on the web in advance and could be subject to change up to the last minute to take into account peer criticism and suggestions. After the workshop is over, these materials (not all of which have made it into this book) remain on the web indefinitely, and the reader can peruse them starting at the *www.ece.sunysb.edu/~serge/FTM.html* home page.

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Part I

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