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Speculations about future directions

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Abstract

Although MBE technology is over a quarter-century old, and has been outstandingly successful in the growth of semiconductor heterostructures, it has a large reserve of as-yet unexplored capabilities left, many of which are likely to play a role in the future evolution of MBE. Developments that can be anticipated are the additions of OMVPE techniques to MBE, for example, for gas etching and surface cleanup. A central problem will be finding MBE-compatible ways to achieve lateral pattern control down to the nanometer scale. Nanoimprint techniques are a good candidate for that. Self-assembled quantum dots will probably give way to lithographically defined quantum dots with much better control over size and placement. Heterostructures of materials other than semiconductors will be increasingly explored, like magnetic and superconducting structures, and may be even organics.

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1. Introduction

Speculations about the future of technology are a hazardous business. Much of the history of long-term technology forecasts has been a history of failures, so I undertake the theme of my title with some trepidation. My only consolation is that I am sufficiently old that it is unlikely that I can be called to account for those of my speculations that will turn out to be wrong. But then, maybe some of them will turn out to be right.

Let me start out by telling you what I do *not* intend to talk about. I will not talk about the growth of MBE as a production technology. Perhaps more importantly—and maybe more surprisingly—I will say almost nothing about the application of MBE to specific individual devices.

One of my reasons for the second restraint is that others, more involved than myself, will present much of the future of specific devices at this conference anyway. But my reasoning goes beyond that—which leads me right to the heart of my intended topic. A study of the history of technology presents staggering evidence for what I have called, on other occasions, *Kroemer's Lemma of New Technology*:

> The principal applications of any sufficiently new and innovative technology have always been—and will continue to be—applications *created* by that technology. [1]

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Now MBE is hardly a new technology anymore, but I am convinced that it has huge reserves left in itself, and that its future probably contains much more than we can currently predict.

But if this is so, then we should not judge the future of MBE technology from the perspective of already-recognized applications, be they heterostructure lasers, HBTs, or what-have-you. Work on those amounts to simply doing something better than we can do it already, but does not represent new applications yet to be *created* by MBE.

I am the first to admit that this is a very speculative proposition, which will not be universally welcome, for two reasons: (a) Applications that will be *generated* by future MBE technology can, by their very nature, not be readily predicted; so I evidently talk about something that is anathema to any control-centered industrial manager. (b) Many of you—perhaps most—are doing MBE in an environment where you do not have the "luxury" of doing MBE in a context of open-ended research, but are compelled to work on very specific applications. But this does not in any way diminish the usefulness—even for those of you—of remaining aware of unanticipated things to come. And there are probably a few members of funding agencies in the audience, who should perhaps be reminded that the current obsession with so-called *strategic research* is little more than a fancy-sounding justification for the discouragement of open-ended research, even though the latter has historically been the ultimate source of most long-term progress. Nobody has said that better than Mermin in his delightful put-down:

> I am awaiting the day when people remember the fact that discovery does not work by deciding what you want and then discovering it. [2]

2. What is MBE?—a broad generic view

My approach to the future of MBE calls for a rather broad generic view of MBE that may go beyond present-day realized capabilities, and before turning to specifics, let me explain this point of view. A good point of departure is to compare MBE with OMVPE. To me, the two have more similarities than differences. Both produce carefully controlled high-quality epilayers from a stream of incident atoms or molecules. The principal applications of both are in growing heterostructure; "plain" non-hetero layers hardly deserve the elaborate equipment. Finally, both are ultimately technologies for chemical reaction synthesis, with the difference that in MBE the reactions take place only on the growth surface itself, while in OMVPE reactions in the gas phase play an important role. All differences arise from a difference in the mean free path of the molecules on their way from some source to the growth surface. In MBE, this path is large compared to the distance traveled, in OMVPE is short. This central difference gives each of the two techniques certain advantages and disadvantages relative to its competitor, and I believe the future development of both techniques will include attempts to minimize the disadvantages by incorporating some aspects of the "other" technique.

Hence I anticipate future MBE equipment that contains, within the same envelope, an OMVPE capability. In fact, combining the two technologies—albeit not in an integrated piece of equipment—is already being practiced: Some of my colleagues at UCSB working on the new nitrides have found it useful to grow structures where an OMVPE nucleation and template growth is followed by an MBE growth. I expect that we will see more of this kind of hybrid growth, using whichever of the two technologies is better for whichever part of the overall structure.

Finally, some indium compounds grow well under In-stabilized or even In-rich conditions, bordering on a new form of beam-fed liquid-phase epitaxy.

3. The lateral resolution problem

MBE has been spectacularly successful in the degree of control and design freedom on the "vertical" scale along the growth direction, down to individual atomic monolayer control, but it lacks—in common with other crystal growth technologies—any significant lateral pattern control *within* those beautiful monolayer planes, especially on the sub-micron scale. These limitations have always been present; they will simply become more severe as we wish to grow increasingly sophisticated structures, especially if the sophistication calls for smaller lateral dimensions, which is likely to be the case. Hence, this can be readily predicted to be one of the dominant developments of the future.

There are two separate aspects involved in this: Multi-step growth, and high-resolution lithography. Let me start with the former.

3.1. Multi-step interrupted-growth techniques

At present, we are still relying almost exclusively on post-growth conventional photolithography. Worse, we are relying on what I would like to call *single-shot* growth followed by lithography-based processing. By the latter I mean a *single* MBE growth sequence—no matter how complicated the internal layer structure—followed by one or more processing steps. What we really need is the capability to have multiple growth sequences separated by processing steps that take place outside the MBE chamber. In Si technology, this capability is routinely present; we would benefit from it, too.

There has recently been some progress in this direction, often referred to as MBE "regrowth" techniques, where a second MBE growth follows some ex situ processing after a first growth. I predict that research in this direction will be one of the important research topics in the years to come.

The problem with all such regrowth techniques is the introduction of interface contamination and defects at the restart interface, especially if ex situ chemical processing has taken place. Simply stopping GaAs MBE growth and exposing the surface to air, without doing anything else, introduces interface defect concentrations (in this case acceptors) exceeding $2 \times 10^{11}\,\mathrm{cm}^{-2}$, with much higher concentrations on processed surfaces. There are of course applications where such defect concentrations are acceptable, for example, when the doping levels on both sides of the interface are sufficiently high to swamp the interface defects. But we do not want to be restricted to such cases; we want to be able to have "invisible" stop-and-restart interfaces, say, inside a laser structure.

Protecting a GaAs surface during ex situ exposure with a film of As, a technique used successfully for GaAs surface studies, is not the answer for processing, because it protects only those parts of the exposed surface that are left alone during; it does nothing for a surface exposed during the processing, for example, by etching.

More research on those interruption-induced defects is called for, along with the development of in situ cleaning techniques within the vacuum envelope. I doubt that "energetic" techniques, such as ordinary sputtering, e-beam bombardment, or ion-assisted etching will be a fully satisfactory answer: These techniques create damage; and while this damage may be acceptable in many structures, it will be unacceptable in others, and if we do not wish to limit ourselves in what we can do, we need some less-energetic techniques, presumably purely chemical or photo-chemical ones.

This is an area where OMVPE has an advantage. Thermal gas etching is a standard part of OMVPE, and I anticipate that it will become more widely accepted in MBE, too. This will obviously not be done inside the UHV MBE growth chamber itself, but in an interlocked chamber for gas processing. Once we have "lost our innocence" by taking this step, I would not be surprised if we equip the gas chamber with a separate OMVPE-like growth capability of its own. In fact, we might wish to mix MBE with OMVPE even for the growth itself, as is already done in some nitride technology.

Once we have "benign" surface cleaning techniques, we will also increasingly employ *pre-growth* patterning technologies, including the patterned deposition of non-volatile metal precursors. Reawakening the old vapor–liquid–solid growth technique on a nanoscale appears a possibility.

3.2. Beyond optical lithography?

When discussing structuring on a nanometer scale, people often propose the use of AFM or

STM tips as quasi-lithographic tools for achieving the desired resolution (and precise placement). The trouble with such probe methods is that they are *serial*, that is, one object at a time. This is fine for building physics research structures that require just a handful of devices, but it is far too slow for structures on the level of complexity as today's integrated circuits. The same comment remains largely true even for serial electron beam writing, except for relatively simple structures. Those who dream about extending Moore's Law by such serial techniques might do well to recognize that anything with less than 10^9 devices per chip is just not interesting as a competition to CMOS, and then do their own throughput calculations—along with what this means for the equipment amortization cost per chip.

For demanding applications involving a large production volume of structures with high complexity, a *parallel* assembly technique is absolutely required. In the last analysis, Moore's Law is simply a statement about the triumph of parallel assembly via optical lithography with finer and finer resolution, which ultimately required shorter and shorter wavelengths. Current trends in mainstream IC technology are toward extreme-ultraviolet (EUV) lithography—at an astronomical equipment cost.

Such costs may be economically acceptable in the IC industry with its huge production volume, but many of the applications of MBE are not of this kind. There is no doubt in my mind that we *do* wish to participate in the push towards nanoscale dimensions. But in this case we should expand our lithography horizons beyond optical lithography, and I do not think that X-ray projection lithography is the answer. There has recently been a rapidly increasing interest in going back some 550 years to Gutenberg's printing press, but on the nanometer scale (see, for example, Ref. [3]). While I am not persuaded that nanoimprinting will take over from EUV lithography in silicon IC technology, I believe that we should consider it as a natural partner of MBE. I can visualize the printing, not only of masks, but of growth precursors that subsequently react with incoming molecular (or atomic) beams.

4. On self-assembled quantum dots

One way around the lithography resolution problem is to work with nanoscale self-assembled quantum dots that form under certain conditions during MBE growth. I am very impressed by what has been achieved with this technology, for example, in the low-threshold laser field; I refer the reader to the numerous papers at this conference for details. But I believe that the approach of using spontaneously nucleated dots is ultimately too limited, or—to put it positively—is only the proverbial tip of the iceberg of what *might* be achievable. If and when we achieve dots with a much better uniformity and with a tightly controlled placement, this will open up a much wider range of capabilities. Many of my QD friends consider 10% (linear) size fluctuations as excellent uniformity; but that means a 30% volume fluctuation, and 20% fluctuations in the quantum energies. There certainly are applications for which this is sufficient, like LEDs and low-threshold lasers without tight spectral constraints, and possibly other devices, especially if the dots need not be electrically contacted individually. But I am convinced that the true potential of QDs will require us to do much better. In order to achieve the kind of size uniformity that will ultimately be required, controlled placement will almost certainly be necessary—which calls for some sort of the *pre-growth* lithography to which I alluded earlier (maybe imprint-based). The sooner we start moving in that direction, the better it will be. And of course, we need not only dots, many applications will require interconnect lines. This calls not only for a nanoscale line technology, it also calls for a predictable placement of the things to be connected.

Ultimately, we will almost certainly want to go to much smaller dots (and narrower lines) than what we are exploring today. At that point, statistical Poisson fluctuations will seriously enter the picture. Any technique that relies on simply collecting the atoms impinging over a certain target area will suffer from these. For example, a Poisson distribution with an average of 1000 atoms will have a standard deviation of ± 33 atoms, or about 3%. At that point we will need growth techniques that are more deterministic in assembling the correct number of atoms.

One obvious way of minimizing Poisson fluctuations would be to first grow extended layers of controlled thickness (something we know how to do very well) and then create the dots (and lines) by "cookie cutter" lithography with nanometer resolution. Furthermore, that continuous layer need not be the final material itself; it could be a precursor, for example, an In film, to be reacted with As after patterning. Regardless of details, nanometer lithography will again be required.

I will probably be told by some that there are no applications for dots this small. That would almost certainly be true *if* we restricted ourselves to the kind of applications that dominate the MBE usage of today. But remember what I said in the *Introduction* about new technology *creating* its own applications. I am convinced that this would be true again here.

5. Beyond "classical" semiconductors

MBE, as a crystal growth technique, started with III–V compounds, especially GaAs and (Al, Ga)As, and that continues to be its mainstream, although by now all III–V compounds have been grown for one purpose or other, almost invariably in the form of heterostructures. The "hottest" III–V materials are of course the nitrides. There has also been significant work on II–VI compounds, but work on other materials is only now becoming a major part of MBE research and technology.

The most active emerging class of new MBE-grown materials is that of magnetic materials, especially magnetic semiconductors. Much of that work sails under the flag of *spintronics*. Inasmuch as there are numerous papers on this topic at this conference, I will simply refer readers to those papers, and only express my expectation that these, and other magnetic materials will be an increasingly important application of MBE technology. What MBE technology, with its tightly controlled and highly instrumented growth procedures, can bring to bear on such materials is not simply an ability to grow thin films with—maybe—better quality. Instead, the emphasis will be on heterostructure involving layers of different materials; including heterostructures with non-magnetic semiconductors. This is in fact a trend we see already.

I am not persuaded that all the applications that have been predicted for spintronics are realistic. But this skepticism should under no circumstances be interpreted as a criticism of the research itself. I am guided here by my own *Lemma of Technological Innovation*, stated earlier, which suggests that this particular new technology, too, will *create* its own applications, which may or may not have anything to do with the predictions made today.

Another class of materials that I believe will play an important role in the future of MBE technology is that of high-T_c superconductors, including superconductor–semiconductor hybrids. Much of my own research during the last 12 years has been on such hybrids, more specifically on so-called *superconductive weak links* in which an MBE-grown heavily modulation-doped InAs quantum well (with AlSb barriers) acts as a coupling link between two superconductor bodies (Nb) deposited on the InAs by ordinary sputtering [4]. The quality of the super-semiinterface has emerged to be crucial, and it would probably be beneficial if the superconductor, too, could be grown by MBE. Given this background, I hope I can be forgiven for saying a few words about the combination of MBE and superconductors.

Some of the high-T_c cuprates, especially YBCO ($=YBa_2Cu_3O_{7-x}$), have been prepared by MBE, but the cuprates are poor candidates for super–semi hybrids: They require deposition (or a post-deposition anneal) in a strongly oxidizing environment at high temperatures, a deadly combination for any classical semiconductor. Nor has the inverse approach of growing the semiconductor on top of the cuprate superconductor been more successful: The semiconductor tends to reduce the superconductor, which destroys the super-conductivity. Perhaps the most interesting (and challenging) superconductor candidate for MBE growth is the new intermetallic (non-oxide) superconductor magnesium diboride (MgB_2), with its remarkably high critical temperature (for a non-oxide) of 39 K. Being non-oxidic, it might be compatible with semiconductors for future super–semi hybrids, an old favorite topic of mine. In fact, initial reports on the MBE growth of MgB_2, at remarkably low growth temperatures ($\leqslant 320^\circ C$) on various substrates, including specifically Si (1 1 1), look promising [5]. Given the low growth temperatures, growth on III–V compounds might be possible, including specifically on InAs, the ideal coupling medium for semiconductor-coupled superconductive weak links.

Finally, I would not be surprised if MBE were applied to organic materials. The driving force to do so would be the tightly controlled and highly instrumented growth procedures of MBE, which might offer capabilities beyond those of classical organic chemistry.

References

[1] H. Kroemer, Rev. Mod. Phys. 73 (2001) 783–793.
[2] D. Mermin, Phys. Today. 52 (1999) 11–13.
[3] C. Kim, M. Shtein, S.R. Forrest, Appl. Phys. Lett. 80 (2002) 4051 (this paper contains extensive references to earlier work. See also a series of conference papers in J. Vac. Sci. Technol. B 19 (2001) 2707).
[4] M. Thomas, H.-R. Blank, K.C. Wong, H. Kroemer, E. Hu, Phys. Rev. B. 58 (1998) 11676.
[5] K. Ueda, M. Naito, Appl. Phys. Lett. 79 (2001) 2046.