Prospects for
Coherent Nano-Electron-Beam Technology

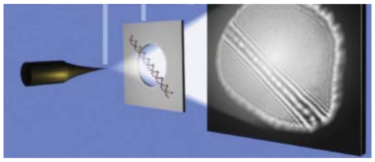
With Potential Applications to Mass-Producible Arrays
of Miniature Electron Microscopes
and Nanoelectronic Devices

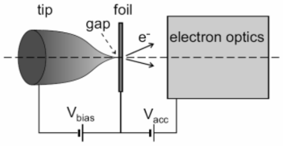
> “The problems of chemistry and biology can be greatly helped if our ability **to see what we are doing**, and to do things **on an atomic level,** is ultimately developed — a development which I think cannot be avoided. … I put this out as a challenge: **Is there no way to make the electron microscope more powerful?**” — Richard Feynman, 1959

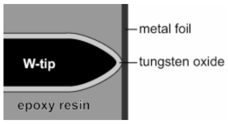
How might {inexpensive and abundant} nano-vision systems based on coherent nano-electron-beam technology become a breakthrough leveraging technology for nano-feedback-based {innovation and mass-production}?

By considering this question:

> “What are the next steps in the following series of nano-electron-beam emitters?”







In addition to suggesting some answers to the preceding question, we will also consider these follow-on questions:

- What are the most practical means for making “industrial strength” versions of {solid-state, low-voltage, and coherent} nano-electron-beam emitters with {atomic-point tunnel junctions and very narrow emission cones}?
- How can we most easily make different types of micro-scale electron microscopes using such emitters?
- Can we make high-performance nanoelectronic {sensors and mixed-signal devices} using collimated coherent nano-electron-beams that are laterally injected into 2-D graphene systems?

(Last revised: 2010-06-25)

Contents

1. Preface

For {economy and explicitness} of expression, I sometimes use “{...}” to visually delimit {lists, compound phrases, long phrases, or other items} — especially when these occur {in mid-sentence, or in combinations}.

This write-up outlines some seemingly exceptionally-promising technological possibilities involving {sources and applications} of coherent nano-electron-beam technology. This technology is beyond my present means to {rigorously evaluate and develop}, although I think there is very strong conceptual case for its likely feasibility.

2. Introduction

There are 2 main reasons that coherent nano-electron-beam emitters are particularly interesting:

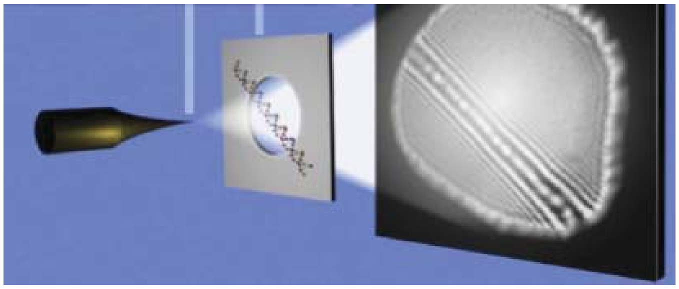
- Nano-imaging: Conventional {scanning electron microscopes (SEMs) and scanning probe microscopes (SPMs)} are outstanding R&D tools. However there still appear to be important intermediate niches where scanning electron microscopes based on {micro-scale, low voltage, and coherent} nano-electron-beam emitters could play important roles. A cost-performance breakthrough in the realm of near-atomic-resolution micro-SEMs could help accelerate nanotech R&D involving many special cases of {nano-manipulation and nano-inspection}.
- Nanoelectronic devices: Electron beam technology once formed an integral part of early electronics technology and then fell by the wayside during the microelectronics revolution. Here again, nano-electron-beam emitters might rejuvenate older electron beam signal processing technology in the form of high-performance nanoelectronic {mixed signal, switching, and data link} systems — except that ballistic transport within 2-D graphene layers could take the place of 3-D vacuums.

If these things are feasible, they could powerfully boost several {technically and commercially} important realms of nanotechnology development. So I’m very interested in encouraging further investigation of these realms. I’m also very interested in collaborating with others having related interests.

Please feel free to share this write-up with others.

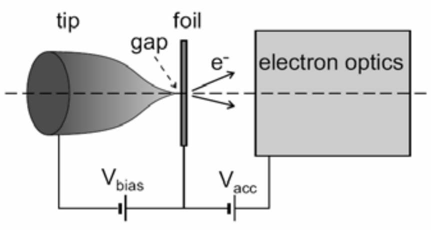
3. Intriguing Experimental Precedents

A process for producing atomically-sharp tungsten tips terminating in a perfect tetrahedron of tungsten atoms was experimentally developed at IBM's Zurich Research Labs in the mid-1980s (Fink, 1986). Further work showed that such tips could produce nano-scale electron beams by means of coherent atomic-point field emission from the tip's apex atom (Garcia and Rohrer, 1989; Fink, Stocker, and Schmid, 1990). The next illustration shows the use of such a tip in a point projection electron microscope (Germann, Latychevskaia, Escher, and Fink, 2010):



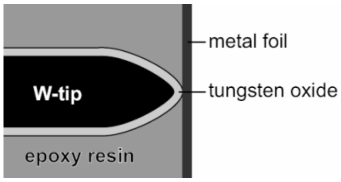
This wonderful system has major practical disadvantages involving the challenging process of forming the special emission tip, plus it requires an ultra-high vacuum to preserve the delicate tip.

An alternative means of generating nano-electron-beams by means of a vacuum tunnel junction and an electron-transparent metal foil is shown below (Borgonjen, van Bakel, Hagen, and Kruit, 1997):



The disadvantages of this configuration are the foil's thickness (reducing beam output and quality) and the foil's tendency to deform (due to high local fields across the gap), which leads to current instability.

A solid-state version of the preceding configuration is shown below (Van Aken, 2005):



The main limitations are the oxide layer thickness (approximately 20 nm) and metal foil thickness (approximately 20 nm). A system where both dimensions could be reduced about and order of magnitude would be vastly preferable.

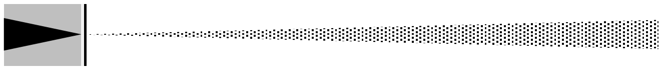
So how can we overcome these limitations to attain the potential advantages of coherent atomic-point emission in a rugged solid-state system?

4. Next Steps

The preceding experimental configurations illustrate some important points:

- An atomic-point source of electrons can be coherent, meaning that the resulting nano-electron-beam can exhibit interference effects. The energy spread of such beams is very low, which reduces chromatic aberrations in electron optical systems.
- Somewhat counterintuitively, at low voltages, some types of very thin metallic layers can be relatively transparent to ballistic electrons passing through them.
- Nano-electron-beams can thus be produced by means of quantum tunnel junctions, albeit past results have not been good enough for practical applications. However, {by using more advanced materials and by substantially reducing critical dimensions}, we should be able to obtain far better results.

We ultimately want a solid-state tunnel junction emitter that serves as an atomic-point source of coherent electrons. Thus we should aim for rugged solid-state tunneling gap (that is similar in scale to that used in a scanning tunneling microscope), such that low-voltage tunneling predominantly occurs through the closest tip atom across a nanometer-scale tunneling gap. One possibility is using a graphene extraction electrode on an insulating nano-layer tunnel barrier, which is contacted by a conducting tip:



Among the possibilities for the conducting tip are:

- using a metallic carbon nanotube (possibly at a slant angle), or
- using a metal dendrite that is electrolytically grown within a solid-state electrolyte support layer (whose activation threshold voltage is well above the emitter's tunnel emission operating point).

Practical considerations may require (for example) {a multi-layer graphene film, a multi-layer insulating tunneling barrier, or a graphene oxide protective overlayer}.

For purposes of early experiments, it may prove easier to fabricate such an emitter upside-down on a sacrificial layer, which can subsequently be removed prior to {inverting and deploying} the emitter.

The operating voltage for nano-electron-beam emission would likely be under one volt (perhaps in the 100-200 mV range), with a very low energy spread.

If suitable types of insulating but very-low-scattering nanolayers (for the energy level of the emitted electrons) can be found, another insulating nano-layer and a graphene accelerating/focusing electrode might optionally be added.

Such coherent nano-electron-beam emitters might be used in various configurations:

- for imaging:
    - the emitter's beam could accelerated and focused with micro-electrostatic lenses for use as a micro-SEM;
    - the emitter could be used in miniature point projection electron microscopes;
    - the emitter could be scanned above a target surface, using a tandem proximal probe system to control elevation;
    - the emitter could be used to explore low-voltage electron analogs of optical near-field sub-wavelength imaging;
- for devices:
    - the emitter's beam could be collimated and laterally injected into variously {patterned and electronically modulated} graphene {sheets and ribbons}, to exploit graphene's remarkable ballistic transport properties for high-performance beam-steering-based {switching and signal processing} functions (such as multiplexers and analog-to-digital converters), among many other things;
    - exploit nano-electron-beam coherence for {interferometric and diffractometric} sensors of {voltage changes, magnetic field changes, nano-mechanical deformations, and other physical properties};
    - use the emitter's beam for remotely {driving and sequencing} systems of nano-electrostatic actuators; and
    - use 20 nm scale (and smaller) nano-imprint lithography to make very high density arrays of such emitters for supplying conventional high current electron beam devices.

The {very small size and very low operating voltages} of coherent nano-electron-beam emitters have some major potential advantages:

- For micro-electron-microscopes:
    - greatly reduced electron beam voltages could be valuable for non-destructive high-resolution imaging of biomolecular materials (such as DNA, proteins, and viruses) without requiring {fixation, metal over-coating, or cryogenic stages}; and
    - greatly reduced electron microscope size means that much lower vacuums (and sometimes atmospheric pressure) could be used in special cases. (Although rugged solid-state emitters might be cleanable, they might need to be periodically replaced, just as tips for scanning probe microscopes are periodically replaced due to wear.)
- For {interfacing and control} issues, the very low operating voltages of coherent nano-electron-beam emitters would be compatible with current-generation integrated circuits.
    - This could later be very advantageous for subsequent mass-production of coherent nano-electron-beam arrays by means of conventional {integrated circuit or MEMS (micro-electromechanical systems)} process technologies — especially when they are adapted to increasingly incorporate graphene {devices and interconnects}.

5. Conclusion

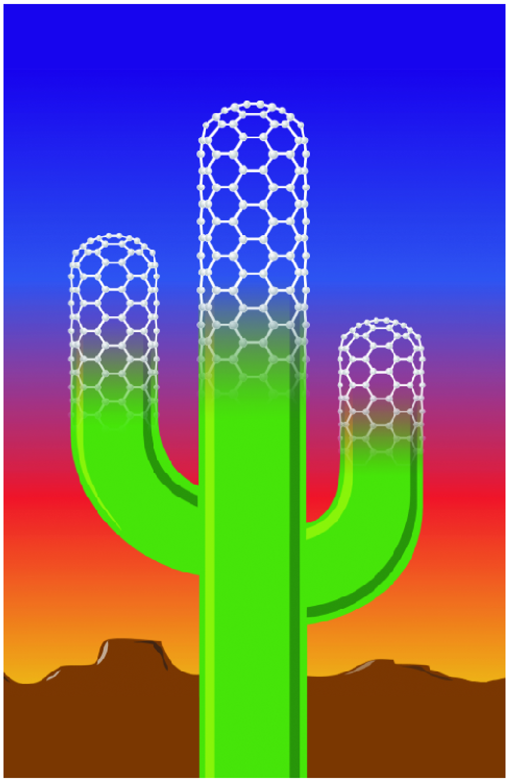
If the briefly-sketched possibilities of the preceding sections are feasible, there will be a vast array of {related and derivative} technologies that could be developed. For example, some additional possibilities include {desktop nano-electron-beam electro-deposition-fastening systems for molecular-scale nanostructure prototyping, desktop ultra-nano-lithography systems, and generating moving nano-scale point light sources for near-field sub-wavelength optical imaging}.

However the first step is to find people with the {interest and means} to {theoretically and experimentally} {explore and develop} suitable coherent nano-electron-beam emitters. I've collected quite a few technical papers that others might find useful for investigating such possibilities.

I'm especially in any technical feedback that could be used to improve future versions of this write-up, which I hope to expand as {time and resources} permit.

Needless to say, I'm also very interested in finding {funding or consulting work} that would allow me to pursue such things full time. Any leads would be greatly appreciated (please see contact information below the illustration).

Thanks.



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