Vacuum Nano Electronics:  
*Back to the Future or Foreword to the Future?*

Vacuum electronics was the first platform for processing electrical signals (amplifiers, filters, etc) and these systems were built using the thermionic vacuum tube — a three-terminal device in a voltage applied to the control grid (plate or gate) is used to control the current at the anode. In the most common configuration, the electronic signal is applied to the control grid (or plate) and the output is taken from the anode. These initial vacuum electronic devices enabled long distance transmission of telephone signals, analog computation, analog control systems and finally the first digital computer system shown in Figure 1.

![Thermionic vacuum tube diagram](image)

**Figure 1:** The first general purpose computer (ENIAC) built using vacuum tubes.

The thermionic vacuum triode is fundamentally a device whose anode signal current depends on the modulation of the density of electrons emitted from the cathode (emitter) by the grid and hence its speed or frequency response depends on the capacitance of the control grid. The quest for higher bandwidth for information transmission led to development of higher frequency devices whose frequency of operation depend on the modulation of the carrier velocity resulting in new architectures (Travelling Wave Tubes, Klystrons, Magnetrons) which enabled the radar and the particle accelerators.
Central to all these vacuum electronic devices is an electron source (cathode). The properties of electrons emitted by the cathodes can be modified by focusing, modulation or acceleration through interaction with other electromagnetic fields. Hence, they are crucial to all electronic devices we make.

Electrons are ejected from metal or semiconductors when they acquire sufficient energy to jump over an energy barrier between the Fermi energy level in the metal and vacuum (thermionic emission, photoemission) or the barrier at the Fermi energy level in the metal is narrow enough for electrons to tunnel through the barrier to take advantage of their quantum mechanical properties (field emission, optical field emission). The general principles for these two broad categories of electron emission (a) “jump over a barrier” or (b) “burrow through a barrier” are depicted in Figure 2. There are a number of other emission techniques which are in essence a combination of these two broad processes — photo-assisted field emission, multiphoton emission and strong field photoemission, thermally enhanced field emission. Related to these types of cathodes are the ones that rely on emission processes over an internal barrier and ballistic or quasi-ballistic transport of electrons in the conduction band of a thin semiconductor layer with negative electron affinity or negative effective electron affinity surface.

Figure 2: Broad categories of electron emission mechanism – emission (a) “jump over a barrier” or (b) “burrow through a barrier”.

Bardeen and Brittain ushered in a new area of electronics in 1948 with their historic paper entitled “The Transistor, A Semiconductor Triode”. This ultimately led the transition from vacuum devices to solid state devices. The transition took a long time because the first solid state devices were neither reliable nor reproducible. The solid-state electronics industry did not blossom until the invention of the integrated circuits which enabled the aggregation of millions (now billions) of transistors on the same chip and sometimes in the same package.
A key enabler was the invention of the associated fabrication platform — the planar process. The industry benefited hugely from the insight by Gordon Moore who observed that the number of devices on IC chip would double every year. A key component to the accomplishment of this vision is the formulation of device scaling law by Robert Dennard which reduced all linear physical dimensions by a factor $\kappa$ while all voltages were scaled by a factor $\lambda$ where $0 < \lambda < \kappa < 1$. These laws guided the integration of billions of devices and hence a lot functionality of the same chip and programmability that we now have today.

The miniaturization and the simplicity of the transistor structure was not lost on device engineers working with vacuum electronics systems. First was the low voltage and low energy required for transistor operation at room temperature and second was the ultimate control of the impact of the surface by making carriers transport occur far away from the surface after passivating the surface with an insulator.

![Image](image_url)

**Figure 3:** From left to right — Replica of the first transistor by Bardeen and Brittain, Silicon fin Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and the 14 nm node; interconnect network for an integrated circuit (IC) and fully packaged microprocessor showing the high degree of device integration.

At about the same time the transistor was being developed, Kenneth Shoulders then at MIT invented a miniature vacuum cathode that is all electrostatic in much the same way as a MOSFET. A horizontal electrostatic field is used to eject electrons from a conducting tip into a vacuum channel and a vertical electrostatic field is used to accelerate the electrons towards a collector or anode from the cathode. Most important is that the device uses very little power as electrons are ejected from the tip using electron tunneling (field emission) in response to electrostatic field at the emitter tip created by a proximate annular gate. In many ways, including structure, the operation of the miniature cathode is similar to that of the transistor with exception of how electrons are injected into the channel (thermionic emission over a barrier for
the transistor vs electron tunneling through a barrier for the field emission cathode) and the channel material (semiconductor for the transistor vs vacuum for the field emission cathode). This concept was further developed by Charles Spindt and collaborators at SRI International to demonstrate the field emission cathode that is based on thin film. The device is highly integrated into arrays using micro- / nano- fabrication techniques that were developed for integrated circuits and transistors. This was perhaps the beginning of the era of vacuum microelectronics and a focus on tunneling as the preferred cathode approach for highly integrated vacuum electronics. Later Henry Gray and collaborators at NRL integrated the anode/collector on the same substrate with the emitter and gate to create a transistor with a vacuum channel with the potential for becoming a vacuum integrated circuit.

**MOSFET vs Vacuum Transistor**

While the operation of the vacuum micro-triode and the transistor both are based on density modulation of electrons, it is instructive to examine a comparison between the transistor and the vacuum micro-triode from the point of view of their application of electronics. Vacuum devices and by extension vacuum microelectronic devices have excellent output circuit (power delivery loop) characteristics—low output conductance, high voltage and high power handling capabilities. However, their input circuit (control loop) characteristics are relatively poor — they have low current capabilities, low transconductance, high modulation / turn-on voltage and poor noise characteristics. Consequently, the last two decades and a half witnessed tremendous research efforts to improve the input circuit of vacuum microelectronic devices for various applications such as flat panel displays, RF signal amplifiers & sources and more recently digital information processing.

Semiconductor devices on the other hand have high current capabilities, high transconductance, low operating voltages, high unity gain cut-off frequency and noise performance. However, they have poor thermal management and are unable to handle high voltages or power densities. Hence, it can be summed up that semiconductor devices have excellent input circuit (control loop) characteristics but they have poor output circuit (power delivery loop) characteristics.

Figures 4 and 5 show the electron energy in the channel of a MOSFET and the vacuum gap of a field emission device. The figures show that electrons are emitted from a source (emitter) over (through) a barrier into the channel. A drain (anode) collects the emitted electrons after they acquired energy from the drift field. In the MOSFET, a controlling gate lowers the barrier to thermionic emission while in the field emission device an extraction gate narrows the barrier to
electron transmission. In both devices the current density is determined by the transmission through the source (emitter) / channel (vacuum) barrier. The figures demonstrate the similarities between the two devices while also showing a major difference — the source (emitter) / channel (vacuum) barrier height, which accounts for a lot of the observed differences in performance of the input circuits.

**Figure 4:** Electron energy in the conduction band of a MOSFET when the device is OFF and ON. Electrons are injected into the channel from the source through thermionic emission over a source channel pn junction.

**Figure 5:** Electron energy in a field emitter showing conditions when the device in OFF and ON. Electrons are injected into the channel by tunneling from the emitter into the vacuum channel.
The Future using the Past as a Prologue

Solid-State transistors are inherently limited by two factors that also contribute to their immense success: They are limited by scattering of carriers resulting in momentum and energy relaxation. Energy relaxation results from emission of optical phonons when carriers collide with the lattice leading to electron velocity saturation at a value determined by the optical phonon energy. Typical optical phonon energy ranges from 0.03 eV in silicon to 0.12 eV in diamond. This limits the maximum velocity that could be attained by electrons (holes) in a semiconductor to a saturation velocity of \(1 \times 10^7\) cm/s < \(v_{sat}\) < \(2 \times 10^7\) cm/s. Consequently, the approach for obtaining higher unity current gain cut off frequency \((f_t)\) is constrained to scaling the transport channel to shorter lengths. Current Si integrated circuits generations have channel lengths of 7-10 nm. Solid State transistors are also limited by the maximum voltage that can be placed across before breakdown occurs due to impact ionization. The maximum breakdown field depends on the bandgap and it increases with bandgap.

Two consequences emanate from these limitations on the performance of the device. The first major consequence is that materials breakdown field which depends on the bandgap is limited to \(3 \times 10^5\) V/cm in silicon and \(10^7\) V/cm in diamond. Scaling the channel length limits the voltage that could be applied to drain (or collector) due to the limited breakdown field. This fundamental limitation is captured by the Johnson Figure of Merit which provides a comparison of the relative performance of a device based on their ability to deliver high power at high frequency in RF/THz devices or the ability to deliver high switching speed with adequate noise margins in digital systems. The Johnson Figure of Merit is given by

\[
J_{FoM} = \frac{E_{BD} \cdot v_{sat}}{2}
\]

where \(E_{BD}\) is the breakdown field of the semiconductor channel and \(v_{sat}\) is the saturation velocity in the semiconductor channel.

Table 1: Johnson Figure of Merit for some semiconductors and nano vacuum channels

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>6H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
<th>Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{sat}) (cm/s)</td>
<td>(1 \times 10^7)</td>
<td>(1 \times 10^7)</td>
<td>(2 \times 10^7)</td>
<td>(1.4 \times 10^7)</td>
<td>(1.5 \times 10^7)</td>
<td>(3 \times 10^7)</td>
</tr>
<tr>
<td>(E_{bd}) (V/cm)</td>
<td>(3 \times 10^5)</td>
<td>(4 \times 10^5)</td>
<td>(2 \times 10^6)</td>
<td>(3.3 \times 10^6)</td>
<td>(&gt;100)</td>
<td>(&gt;100)</td>
</tr>
<tr>
<td>Johnson FoM</td>
<td>(4.8 \times 10^{11})</td>
<td>(6.4 \times 10^{11})</td>
<td>(6.4 \times 10^{12})</td>
<td>(7.4 \times 10^{12})</td>
<td>(2.4 \times 10^{13})</td>
<td>(4.8 \times 10^{14})</td>
</tr>
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The second major consequence is the complexity of the electrostatics of the devices which prevents complete isolation between the output port and the input port. Complete isolation between the output and input ports is crucial for obtaining high intrinsic gain. The device does not behave as an ideal voltage controlled current source rather it behaves as voltage-controlled resistor. This is because the proximity of the controlled terminal (drain/collector) to the source/emitter leading to a two-dimensional electrostatic potential profile and degradation in the isolation source to channel (emitter to base) barrier from the influence of the controlled electrode. This has led to more complex device geometry such as the FinFET to mitigate these deficiencies.
These issues suggest that we should *go back to the future* – the use of vacuum as channel of the transistor. Why? There is no scattering in the vacuum channel (ballistic transport) and there is no impact ionization in a vacuum channel (no channel breakdown).

Recent work at NASA is exploring the nano vacuum channel transistor (NVCT) in which the transport channel for a MOSFET is replaced by vacuum as long as carriers are efficiently injected into the channel. Carrier injection into the channel is by field emission. There are several questions that are being posed by device physicists/engineers:

- Is there a way to combine the excellent input (control loop) characteristics of the semiconductor devices with the excellent output (power delivery loop) characteristics of vacuum devices?
- Is it possible to take advantage of the lack of scattering in the channel of the NVCT to obtain high circuit speed and efficient power delivery?
- Is it possible to obtain the very high level of integration?
- Is it possible to build a microprocessor based on the NVCT?
- Given the fact the device dimensions are much smaller than the mean free path of electrons at 760 Torr, is it possible to build a microprocessor that operates at 760 Torr? Ambient?
- Is Empty State Electronics possible?
- What are the obstacles to reliability?

This talk will explore these questions and present a view could be described as “*back to the future*” or “*foreword to the future*”.