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Nano phototubes-A new approach towards electronics

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***Abstract-* A new electronic device, the "Novatron", is presented. The Novatron is a nano-scale triode vacuum tube in which electrons are liberated from the cathode via photo-emission instead of thermo-emission. The new technology enables the production of very high frequency devices approaching terahertz frequencies and opens new venues for integration of electronic elements.**

The first generation of electronics was based exclusively on vacuum tubes, where non-linear current-voltage behavior is obtained by manipulating free electrons, liberated thermally from a metallic cathode.[1] The second generation of electronics is based on semiconductor technology, where non-linear current-voltage behavior is obtained by manipulating electron (and hole) movement inside solid-state matter.[2] This transition brought about great advantages. However, one important negative characteristic of semiconductor electronics is that the capability for generating power diminishes strongly with increasing frequency. For example, power from GaAs and InP Gunn devices has been shown to scale, at best, as $1/f^3$, where f is the frequency.[3]

We present a new electronic device, which we call the "Novatron", as a practical solution to the above dilemma. The Novatron is, at heart, a triode vacuum tube, but differs from the historical one in two critical aspects. First, it is an on-chip, nano-scale device. Thus, by leveraging modern semiconductor manufacturing technology we retain the capability for integrated circuit design with small critical dimensions. Second, electrons are liberated from the cathode via photo-emission instead of thermo-emission, thus eliminating a major obstacle to both device design and device reliability. The new technology enables the production of very high frequency devices approaching terahertz frequencies and opens new venues for integration of electronic elements.

A key advantage of semiconductor-based technology over the vacuum-tube based one was that it facilitated large scale circuit integration on the same chip, thus ushering in the era of modern electronics as we know it today.[4] The detailed performance of semiconductor-based electronic devices in general, and transistors in particular may vary greatly, depending on the semiconductor used,

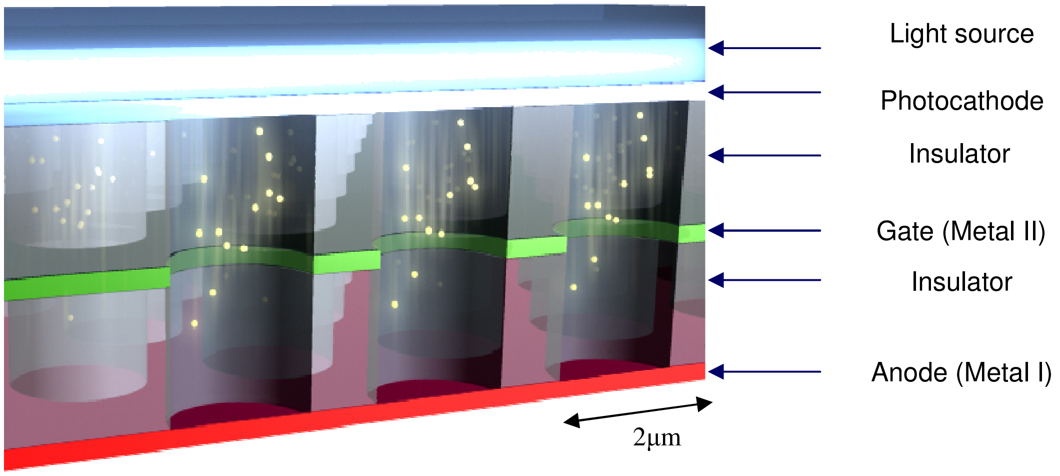

Figure 1: A scheme of the Novatron structure

device details, and level and type of integration. However, there is a fundamental limitation irrespectively of such details. In order to increase the operating frequency, the device size must be scaled down so as to reduce capacitance and charge carrier transit time. But it is precisely this scale-down that limits power extraction from the device. Reverting to ballistic transport in vacuum allows one to reduce the above difficulties considerably, as they all essentially arise because charge carrier transport is done in matter.

In the Novatron, shown schematically in Figure 1, electrons are liberated from a photocathode, illuminated from the back by an appropriate light source. Electron motion then proceeds in vacuum between cathode and anode, with a metallic ring serving as the gate. A practical realization of this scheme requires two major components: A die on which the anode and gate are structured and a glass window on which the photocathode is evaporated. Because of the immense know-how existing in silicon based micromachining we chose silicon as the die on which the device was patterned.

In one possible micrometer scale realization of the first component, a ~2 μm thick TiN protected Al layer, to serve as the anode, was deposited on the silicon substrate. A ~1.5 μm thick SiO_2 layer was then deposited to insulate between anode and gate. Next, a 0.25 μm of metal layer, to serve as the gate, was deposited. Next, (rectangular or circular) cavities, with typical width of ~1.5÷3 ~1.5 μm, were etched down to the anode surface. Identical cavities that share the illumination are connected in parallel to form one device. Generally, as many cavities as needed or as few as one cavity can be manufactured as an independent device. Several such devices, electrically insulated from each other, were manufactured on each Si chip.

To realize the second component, an Sb-Cs photocathode [5] was evaporated on sapphire. The two parts were then attached by soldering at the perimeter. The entire process of photocathode evaporation and sealing was done in one sequence inside the vacuum environment, resulting in a ~5 μm distance between cathode and anode. Note that because of the short cathode-anode distance, the vacuum required is moderate. At a cathode-anode distance of ~10 μm, simple mean free path considerations show that a pressure of up to 10 mbar of nitrogen can be maintained without interfering with electron motion. Naturally, any gas present should not interact deleteriously with electrode surfaces, notably that of the photocathode.

For demonstrating the successful triode operation of this device, a sealed complete device was illuminated via the sapphire window at normal incidence to the surface with a 405 nm laser at a net illumination intensity of ~40 mW. For each measurement, the laser beam was aimed at a different device. The laser beam was ~1mm in diameter, which is about three times as large as the overall lateral dimensions of the device. Anode-cathode DC current-voltage curves, for various gate voltages, obtained under continuous laser illumination, are shown in Figure 2. A significant gate effect is readily observed.

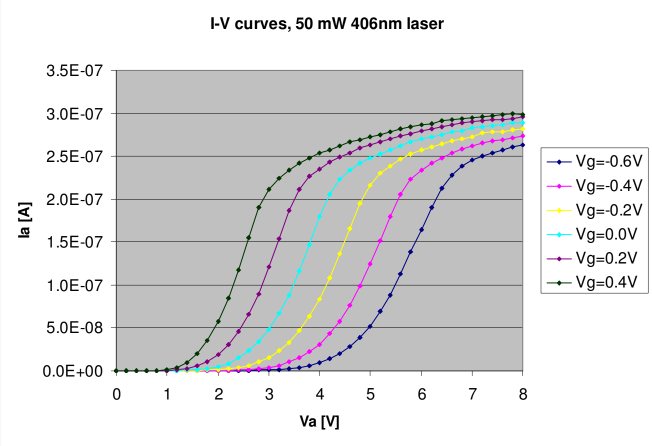

Figure 2: The measured I-V curves for different gate potential for devices shown schematically in Fig. 1.

The measured results were compared with numerical simulations that calculate electric fields and electron trajectories, given a configuration of biased electrodes and particle initial conditions (and neglecting space charge effects), by solving the Laplace equation. In the simulations, (performed using the SimIon package [6]), a model with the actual device proportions and voltages was used. The actual and simulated data agree very well with each other. Preliminary AC measurements with ~KHz frequencies, at a DC bias of 0.2V and 3V for the gate and anode, respectively, showed gate signal inversion and gain (of ~1.75 at 2.5 KHz), clearly establishing successful AC triode operation.

Having proven the concept of the Novatron, we turn to discussing its advantages in terms of reliability and of enhanced functionality. In principle, triode operation can be attained using electrons obtained from thermoemission, field emission, or photoemission. Thermoemission was the mainstay mechanism for the historical vacuum tubes, but this resulted in major reliability and integration issues.

Field emission does not pose major hurdles to integration and has therefore received considerable attention, also in the context of miniaturized vacuum tubes.[7] However, use of field emission as the electron-generating mechanism does raise serious reliability issues. The main problem has been found to be cathode deterioration due to positive ion bombardment.[8] This issue is exacerbated in field emission because the electric field, by construction, focuses the positive ion to the emitting tip(s).

However, this problem is not inherent to photocathodes, where positive ions bombardment can be avoided entirely by working at low voltages such that ionization of the residual materials inside the sealed device is small or negligible. Importantly, photocathode reliability issues have been raised in the literature, especially in the context of low illumination intensity image intensifiers, but always with high operating voltages. Indeed, we used a 455 nm light emitting diode with a total light power of 0.5W to illuminate the glass body of an RCA-929 phototube (S-4, reflective photocathode with peak sensitivity at 420nm), subjected to a bias of 24V. After a few hours during which a ~10% decay in current was measured, the photocurrent was stable at a level of ~0.9 mA for ~12 months (and running), with fluctuations of a few percent at most, which we attribute to instabilities in the illumination source.

In terms of new functionality, we believe that a major advantage of the Novatron is that it can be used successfully for high-frequency electronics, possibly approaching 1 THz.

A different arena where use of Novatron technology combines the best of the vacuum tube and integrated circuit worlds is immunity to damage from an electromagnetic pulse (EMP). In, e.g., a typical semiconductor-based high-frequency receiver, the low-noise amplifier in the first stage is coupled directly to a receiving antenna which has as appreciable area and is hence susceptible to EMP. The transient current that may flow in a semiconductor subjected to EMP in this way is almost certainly sufficient to cause destruction. In contrast, vacuum tubes, by construction, cannot experience more current that their saturated cathode can supply, i.e., they then act as constant-current sources and hence are naturally dissipation-limited.

Finally, Novatron technology may also offer qualitatively new functionality. One such possibility is the integration of several levels of logic operations in one device.

In conclusion, we have presented and experimentally verified a new concept for electronic devices based on nano-scale vacuum phototubes. Furthermore, we have explained how use of this approach can bring about major quantitative or even qualitative advantages in several challenging arenas of modern electronics, including high-frequency, high-power circuits, electromagnetic-pulse-safe devices, and high complexity logic circuits.

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