Solid-state physics

Switch as switch can

from H.L. Störmer

A NEW candidate has become prominent in the highly competitive race for the fastest switch in electronics, the record for which currently stands at about 10 picoseconds[1]. While superconducting devices have been the undisputed leaders for many years, semiconductor devices have recently caught up and even surpassed them in speed performance. Superconducting devices remain unchallenged in their low power consumption, but require to be cooled close to absolute zero. Semiconductor switches, on the other hand, will function at ambient temperatures — though cooling improves their speed and power consumption.

Because each parent wanted to baptize its own child, the present winner runs under various pseudonyms (reviewed in ref. 2): high-electron-mobility transistor, two-dimensional electron gas field-effect transistor, modulation-doped field-effect transistor (MODFET) and selectively-doped semiconductor heterojunction transistor. The superiority of this device is based on a technique dubbed modulation-doping[3], creating a thin (two-dimensional) sheet of highly-mobile electrons at the interface between two semiconductors. But its lead is short. Traditional silicon-metal-oxide-semiconductor field-effect transistors (Si-MOSFET) are close behind, carrying with them the weight of a mature technology. And new devices are on the horizon, the heterojunction bipolar transistor[4] and the metal-base transistor[5] being recent contenders.

On this busy stage, a new actor has now appeared: the velocity modulated transistor (VMT). Its advocates promise a sub-picosecond electrical response, and a recent paper by K. Hirakawa, H. Sakaki, and J. Yoshino[6] contains experimental data substantiating one of its ingredients. The basic idea is simple and has been stated in various disguises, but the recent publication pushes it into the limelight.

Virtually all semiconductor switches are transistors. These are three-terminal devices characterized by an in-terminal, an out-terminal and a control-gate in between, which can enhance or suppress the flow of carriers from in to out. The gating action is provided electrically by applying a voltage or a current to the gate terminal. The gate controls the conductivity σ of the semiconductor, where $\sigma = ne\mu$. Here n is the density of carriers in the material, e is the electronic charge and μ is the mobility. In general, variations in σ can be induced by a variation of the carrier density n, or by a variation of their mobility μ. All traditional transistors are of the first kind: the predominant action of the control gate is to vary n, though invariably μ is also affected. The new proposal is to attack the carrier mobility μ, leaving n fixed. Since, for a given electric field, the mobility is proportional to the average carrier velocity, the effect is termed velocity modulation. What is the advantage over density modulation?

Density variations require carriers to be pumped in and out of the system. Carriers have to be displaced over distances as large as the dimension of the device. This requires time. Modulation of the carrier velocity is subject to fewer delays and, hence, the device speed can be considerably enhanced. How does one change the velocity of the carriers? Following Sakaki[7], the device is constructed in such a way that the action of the control gate is to move the carriers from a low-loss region into a high-loss region. Increased carrier scattering will reduce their average velocity and produce the desired effect. The actual distance that carriers will have to travel from the high-mobility to the low-mobility region can, in principle, be kept exceedingly small[7,8].

Hirakawa *et al.* use a traditional GaAs-(AlGa)As MODFET to establish the principle of the VMT. Field effect transistors are basically parallel plate capacitors of capacitance C embedded in a semiconductor. Conduction along one of the plates (channel) is controlled by a bias voltage ΔV applied to the opposing plate (gate electrode). The simple capacitor equation predicts a carrier density variation of $\Delta n = \Delta VC/e$ and, hence an associated variation of the conductivity $\sigma = ne\mu$ in the channel. Operated in this way a MODFET represents a traditional 'density-modulated transistor'.

For their demonstration, the authors used an additional feature of this device. In a MODFET, the channel consists of a low-density ($n \simeq 10^{12}$ cm^{-2}) two-dimensional carrier system confined to the interface between two semiconductors, GaAs and (AlGa)As. The metal gate electrode covers the opposite side (front side) of the thin (AlGa)As layer. The carriers reside on the GaAs side of the interface being pulled against it by electrostatic forces. Carriers are free to move along the interface and are quantum-mechanically confined in the perpendicular direction. Since the (AlGa)As is heavily doped with impurities, close proximity of the carriers to the interface increases carrier scattering, while further separation from the (AlGa)As material reduces it. The distance between carriers and interface can be controlled by a second electrode placed on the GaAs side (back) of the structure[9]. Its effect is to push the carrier more or less strongly towards the scatterers.

Applying a combination of voltages to back-gate and front-gate, the average carrier mobility can be varied while the carrier concentration in the channel remains fixed. A similar arrangement (substrate bias) is commonly used to achieve this effect in Si-MOSFETs[10] but the mobility variations are not very strong. In the MODFET structure, Hirakawa *et al.* were able to modulate the conductivity of the channel by up to 56 per cent without actually changing the carrier density. To achieve this control, the carriers had to move by less than 0.01 μm towards the interface, compared with approximately 1 μm in typical state-of-the-art density-modulated transistors. Hirakawa *et al.* postulate switching times as short as sub-picoseconds, a decrease by more than a factor of ten over the fastest present devices. But, for the time being, this is not substantiated.

Will it work? No fundamental law of physics forbids it, but at this juncture I see several significant hurdles. A 56 per cent conductivity variation is sufficient for intial demonstration purposes, but engineers would eventually want to see a 100 per cent variation. This would require some very strong scatterers — strong enough to bring the current essentially to a stop. At present it is difficult to imagine this. A second electrode (back-gate) adds considerable complexity, in particular since it has to be buried under the device to bring gate voltages to an acceptable level. The present experiments were performed with very small source-drain electric fields where the concept of mobility is justified. Fast devices function at exceedingly high fields where this concept fails and a constance carrier velocity is approached. Can this saturated drift velocity be modulated in a similar way? It is hard to see a mechanism. In general it seems that as devices become smaller and smaller, and approach the region where carriers in a transistor experience only a few scattering events on their way through the channel, a sensible separation between 'density-modulation' and 'velocity modulation' will eventually disappear.

In one picosecond, light travels 300 μm, which is the distance a signal travels within one switching cycle of such a device. Sit back and think how you would design a computer with such blinding speeds. ☐

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