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MRS Bulletin

Energy-efficient electronics science: Searching for a low-voltage switch

Moore's Law of miniaturization may be coming to an end, but there remains the prospect for further reduction in energy consumption in electronic chips by many orders of magnitude. Indeed, the energy used to manipulate a single bit of information is currently ~10^5 times greater than the theoretical limit. Progress demands a further improvement in material interface defect density, beyond what we have ever achieved before.

While logic and storage are becoming ever more efficient, on-chip communication, whether by wires or by optical waveguides, is the main energy problem. In this viewpoint, transistors are communication devices rather than logic devices. Sensitivity, allowing low powering voltage, becomes the primary figure of merit, while carrier mobility is less important.

In large measure, we have become too dependent on the transistor. As splendid as the transistor has been in defining the technology of our age, it suffers from a serious drawback. Its conduction is thermally activated and presently requires a powering voltage of approximately ~0.8 volts to provide a good On/Off current ratio. On the other hand, the wires of an electronic circuit could operate with a very good signal-to-noise ratio, even at powering voltages lower than 10 mV. Since power is proportional to voltage squared, we are currently penalized by up to ~10^5 in energy consumption.

A more sensitive, lower-voltage switch is critically needed as the successor to the conventional transistor. Among the avenues being pursued are new, more sensitive semiconductor switches; sensitive nanomechanical switches; few-photon optical communication to replace electrical signaling via wires; and magnetic switches actuated by small currents on wires, exploiting, for example, the spin Hall effect.

A much-studied candidate for the new, more sensitive electronic switch, a tunnel field-effect transistor, illustrated in Figure 1, is a desirable switching principle based on sharp band edges.

Unfortunately, current device properties are more consistent with Figure 2, which is beset by interface defects. The history of electronic materials is replete with the challenge of reducing interface state density. Indeed, that is what held up the development of the original field-effect transistor until 1965. This time, the problem is

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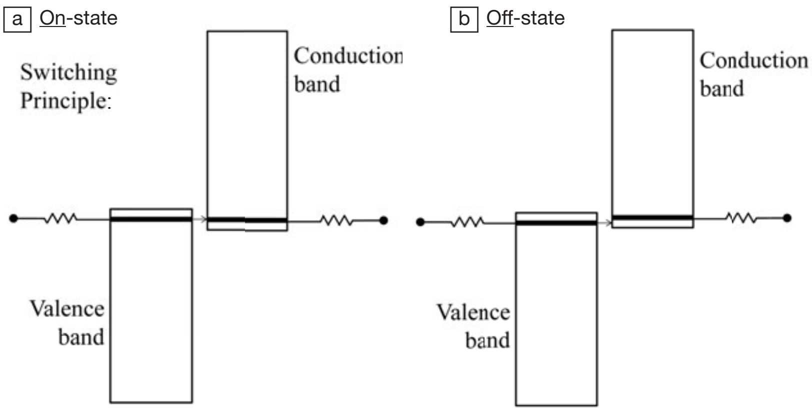

Figure 1. Tunnel switching mechanism: (a) When a valence band edge aligns with a conduction band edge, current can flow. (b) With sharp band edges, a slight misalignment of band-edge energy could stop the current flow.

that the quantum density of states in the conduction band of Figure 2 is ~10^{12} states/cm^2/eV. But the undesired interfacial defect density is not much better than ~10^{11} states/cm^2/eV, producing, at best, a 10:1 On/Off ratio. This is not nearly good enough. Materials science must embark once more on a quest for lower interface density between semiconductors, lower than we have ever achieved. This will require new materials.

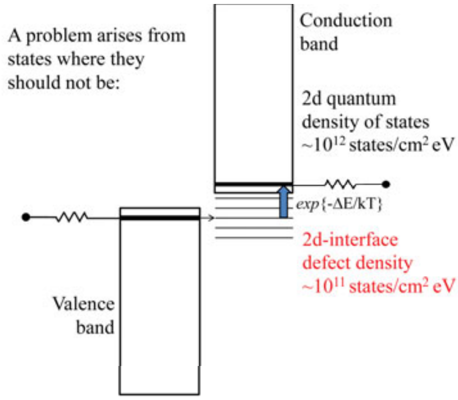

Figure 2. Tunneling-assisted current generation from shallow traps has emerged as one of the major undesired leakage mechanisms in tunnel field-effect transistors. This is a two-step process, tunneling followed by thermal activation. It produces a leakage current that prevents sharp switching.

We should welcome the new monolayer semiconductors, MoS_2, WSe_2, etc. These can be entirely covalently bonded, in which case there might be fewer interface defects. Another possibility is graphene, but not the semi-metallic sheets. Consider rather the semiconducting graphene nanoribbons, which can be synthesized from molecularly purified precursors, in principle, providing sharp energy levels and very low defect densities. There are many other possible material systems that could show an interface defect density below what we have become accustomed to in conventional electronics. If we can provide the requisite interface quality, we could embark on the next stage in electronics, the reduction of operating voltage and power by many orders of magnitude.

Eli Yablonovitch

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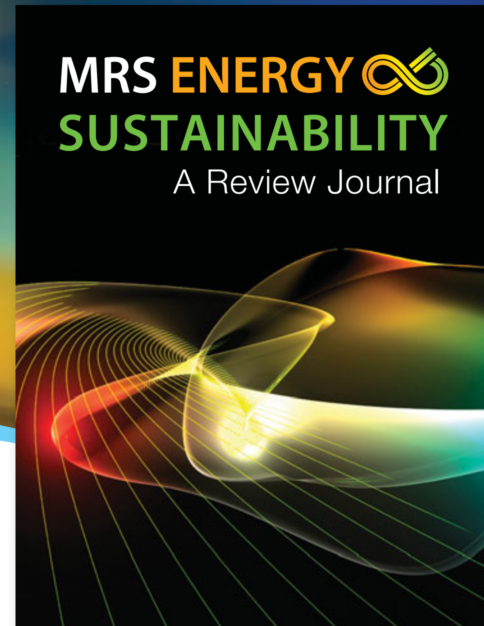

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