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Tunnel structures and devices over the coming decade

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Over the past 25 years, much new physics and many new device ideas have emerged from research using semiconductor heterojunctions. Quantum mechanical tunnelling through thin barrier layers has featured strongly in that research. While some striking device figures-of-merit have been reported, heterojunction tunnelling devices are not yet exploited commercially. Some reasons for this are put forward, together with prospects for tunnelling devices over the coming decade.

1. Introduction

Since the first paper on semiconductor superlattices by Esaki & Tsu (1970), the number of published papers on semiconductor multilayers has grown very rapidly (as measured by citation index entries for example). Research has covered materials, physics, technology and devices. The physics principle of quantum confinement of carriers, either by Coulomb charge at a heterojunction or by a pair of heterojunctions making a quantum well, has produced much interesting physics, some of which is exploited in the high-electron mobility transistor and the quantum well laser. Of order 10^7 of both these devices are sold worldwide each month, and both for approximately \$1 each. The physics of tunnelling in semiconductor heterostructures is very exciting, and we shall see ample evidence of this at this meeting. Tunnel structures are of sufficient materials quality that they are used as a laboratory for investigating physics, for example, magnetotunnelling spectroscopy of energy levels miniband formation, electron–electron and electron–phonon interactions, and quantum chaos. However, there are no sales of devices that rely for their characteristics on quantum mechanical tunnelling, even though some striking figures-of-merit have been reported from prototypes. Why is this so, and what are the prospects for tunnelling devices over the next decade?

2. Contemporary critique of tunnel devices

Several reasons are advanced to explain the absence of commercial tunnelling devices.

(i) The exponential sensitivity of currents to layer thicknesses is not a good starting point for achieving the uniformities demanded for mass-produced devices. In the one published study, the peak current density of resonant tunnelling diodes, taken from one of 15 wafers grown to the same specification during the course of a year, exhibited 20% wafer-to-wafer and 10% on-wafer variability (Mars *et al.* 1993). Field emission electron source arrays is another technology based on tunnelling elements having

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continuing problems of uniformity. Note that quantum confined energy levels are not exponentially sensitive to layer parameters, and they are also relatively tolerant of atomic scale fluctuations.

(ii) It has not been shown that design and fabrication of tunnel devices to an agreed current–voltage characteristic can be achieved, with adequate simulations and multilayer qualification methods to allow reverse engineering. Using a simple microwave detector diode (the ASPAT diode of Syme (1993)) as an example, simulations show that monolayer variations of barrier thickness from the specification cannot be tolerated (Wilkinson *et al.* 1996). Furthermore, the ability adequately to qualify a wafer is unproven by any combination of techniques (let alone a non-destructive, wafer mapping technique). The composition and doping profiles, and their mutual registry, are required with monolayer precision. Any difference between simulation and experiment cannot be attributed unambiguously either to the difference between the as-grown structure and that specified on the one hand, or to limitations in the simulations on the other (Kelly & Wilkinson 1996).

(iii) The devices have inconvenient impedance parameters that militate against their use in hybrid and monolithically integrated circuits. While the detector and varactor diodes have convenient RF parameters, the sources have low impedances, coupling to 50 Ω circuits and stabilization against low frequency oscillations is only achieved at the expense of an unacceptable loss of efficiency (Kidner *et al.* 1990). Specific circuit redesign will be required.

(iv) Tunnel-based microwave sources deliver too low levels of power (microwatts instead of milliwatts) to be useful. There are two contemporary trends strongly favouring tunnel devices for the future, especially in the context of mobile and portable communications. First, there are techniques for increasing output power, such as the incorporation of transit layers to lever up the voltage swings, thereby precluding very high frequency applications (Javalagi *et al.* 1992), and second, the new generations of mixers and detectors are demanding much less local oscillator power (Kearney and Dale 1990).

(v) There are no applications for devices operating above 100 GHz, where the speed attributes of tunnel devices hold up better against the competition from more conventional devices. This is a chicken-and-egg situation, as the lack of devices has limited the opportunities for trial applications. Plasma diagnostics, chemical analysis and ozone monitoring are just three applications waiting for efficient cheap and reliable devices operating above 150 GHz.

(vi) In applications of vertical tunnel structures in logic devices, the strictest uniformity of device performance may not be necessary. At present progress in mainstream transistor technologies is not challenged by offering multifunctionality within devices.

3. Prospects for the future

While the future directions of mainstream silicon microelectronics look uncertain beyond 2010, the prospects for tunnelling devices seem relatively brighter in the short term.

(i) Mainstream electronics will demand tunnel-type structures. The gate oxide of the 0.1 μm transistors required for silicon CMOS in 2007 is only 3 nm thick. Tunnelling currents (e.g. leakage to the gate) place limitations on the range of device

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voltages that can be tolerated. A successful tunnel-type device technology would offer precise control over layer thicknesses and fluctuations in thickness.

(ii) The historical trend of moving upward in frequency has no intrinsic reason to stop at 100 GHz. Tunnel-based devices look relatively more promising at higher frequencies, although just when such devices will be needed is less certain. Tunnel devices have much to offer given the contemporary move to mobile and portable electronics, low power consumption, high efficiency and low noise, compared with the competition (see § 2(iv) above).

(iii) Many attractive attributes of tunnel devices, e.g. their incorporation within transistors to produce a multifunction capability or into light emitters to tailor optical their properties, may in time come to offer the competitive edge when the surface area on a chip becomes a premium.

(iv) The required disciplines for growth and qualification of tunnel-based multilayers are beginning to feature strongly in contemporary R&D programmes in materials.

One hopes that these factors will be enough to lead to a breakthrough in the commercial exploitation of semiconductor tunnelling devices within a decade. If tunnelling cannot be tamed, then mesoscopic devices (i.e. those exploiting effects in structures that are of nanometre length in all three spatial dimensions) will never be manufactured by conventional routes.

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