father, brother or son rather than a random male in the population if $(1-d)^3/4 > \frac{1}{2}$, or $d < \frac{1}{3}$.

Given that the reported estimates of inbreeding costs are probably too low, it might therefore be expected that matings between close relatives should be rare in natural populations, and that mechanisms of inbreeding avoidance should exist. Recent surveys demonstrate that such matings are indeed rare, and there is scarce but mounting evidence of inbreeding avoidance[15,16].

What is the reason for the variation in the costs of inbreeding found among mammals? Because there are no obvious correlates of this variation, it is still not possible to predict the likely costs of inbreeding for any particular species. The previous genetic structure of populations may underlie part of the variation. If a population survives the initial inbreeding depression following a bottleneck, and the deleterious recessive alleles are eliminated in the first few generations, for example, then subsequent levels of inbreeding depression can be considerably lower. Such a situation is believed to have occurred in cheetahs. But the effects of inbreeding depression are not expected to be eliminated in such populations. Indeed, outcrossing in regularly self-fertilizing populations can result in a significant fitness gain[17].

The widespread and usually high costs associated with inbreeding support the view[18] that inbreeding avoidance should be one aim in developing zoo-breeding programmes. But demographic factors may be more important than genetic factors in determining the fate of small natural populations[19]. An example is the case[19] of the little spotted owl *(Strix caurina occidentalis)* — a territorial forest-living bird found in north-west North America — whose future is threatened as its habitat is destroyed by the forestry industry. The original management plan developed by the US Forest Service was designed to protect the territories of about 500 birds on the assumption that this would maintain sufficient genetic diversity in the owl population.

But, using demographic models, Lande argues[19,20] that suitable habitat is too widely dispersed to prevent the loss of local populations and eventual species extinction. Despite the undoubted value of estimates of inbreeding depression for understanding the rules of mate choice, there are other crucial variables in the calculations that should be used to provide guidelines for successful management of natural populations. □

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Microelectronics

Fast switching with novel diodes

Serge Luryi

FOR most two-terminal electronic elements (diodes), increasing the voltage applied across them increases the current that they pass, although not necessarily in a linear (ohmic) fashion. But certain semiconductor diodes exhibit a 'negative differential resistance' effect, in which the current decreases with increasing bias voltage. Placed in a resonant circuit and biased into a suitable voltage range such a diode amplifies any circuit oscillations, rather than damping them as does a normal resistance. The classic example of such an element is the Esaki tunnel diode[1], used as a fast, low-noise microwave generator and amplifier. Resonant tunnelling quantum-well diodes are similar devices that promise to operate at frequencies as high as 10^{12} hertz. J. F. Whitaker, T. C. L. G. Sollner *et al.*[2] have used such a diode in a switching circuit and show that it has a rise time of only 2 picoseconds — the fastest switching event yet observed for an electronic device.

The double-barrier, or quantum-well, diode was first proposed as an electron interferometer analogous to the optical Fabry–Perot étalon. In early proposals[3,4], workers considered a semiconductor–metal–semiconductor structure in which the central metal layer would be a resonator for the quantum-mechanical de Broglie waves of the electrons that tunnel from one semiconductor layer (emitter) into the other (collector). At certain energies of incident electrons, the amplitude of the de Broglie waves in the resonator builds up to the extent that these waves leaking in both directions cancel the reflected waves and enhance the transmitted ones.

Thus in the absence of scattering, a system of two identical barriers is completely transparent for electrons entering at a resonant energy and the total transmission coefficients plotted against the incident energy have several sharp maxima. With scattering, the electron wavefunction need not be coherent across the entire double-barrier structure and the electron transport occurs in two sequential tunnelling steps. Negative differential resistance (NDR) is the property of the first of these steps, involving the tunnelling from a three-dimensional electronic system in the emitter into a two-dimensional system of states in the narrow resonator. The subsequent tunnelling into the collector is an uncorrelated event.

Practical resonators followed the pioneering work of Tsu and Esaki[5], who showed that an infinite heterojunction superlattice — comprising a periodic sequence of narrow layers of alternate semiconductor materials — should have a state of negative conductivity (and would also sustain oscillations induced by an electronic field). In subsequent work[6] on finite superlattices, the same authors showed that NDR is possible in double-barrier quantum-well structures, a prediction confirmed experimentally with $GaAs/Al_{0.3}Ga_{0.7}As/GaAs$ double-barrier diodes[7] and GaAs/AlAs superlattices.

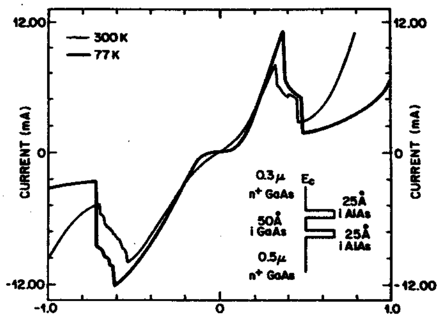

Fig. 1 Current–voltage characteristics of a typical resonant-tunnelling diode (after ref. 11). The structure contains an undoped 5 nm-thick GaAs quantum well clad by two undoped 2.5 nm-thick AlAs barrier layers, as illustrated in the insert. Thermal effects (lattice vibrations) lead to a finite current between the peaks.

Sollner and co-workers later reported[8,9] microwave activity in quantum-well diodes with clear NDR characteristics at 77 K. They showed that the diode could operate as a detector and mixer of far-infrared radiation at 2.5 terahertz (10^{12} Hz), and obtained active oscillations at frequencies up to 18 gigahertz from a diode mounted in a resonant cavity.

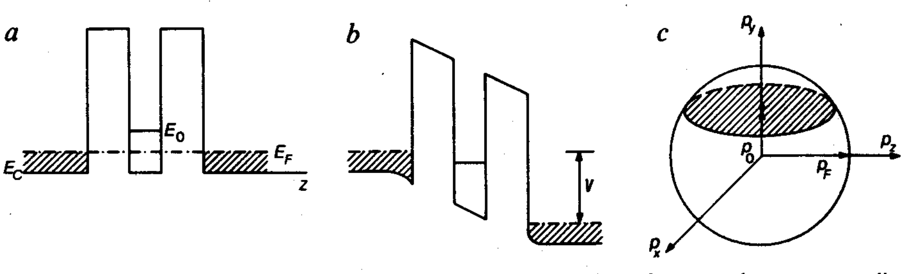

Fig. 2 Operation of a double-barrier resonant-tunnelling diode. *a*, The electron energy diagram without biasing. *b*, With an applied bias V, for which the energy of certain electrons in the emitter matches unoccupied levels of the lowest sub-band E_0 in the quantum well. *c*, The 'Fermi sphere' of occupied states for the three-dimensional electron 'gas' in the emitter — the locus of points in the momentum (p) space with $p_x^2+p_y^2+p_z^2 \leq p_F^2 = 2\ mE_F$ (m is the electron mass). Conservation of the lateral momentum during tunnelling requires that only those emitter electrons whose momenta lie on a disk $p_z = p_0$ (shaded) can tunnel into the quantum well. Here, $p_0^2/2m$ is the energy separation between E_0 and the bottom edge E_c of the conduction band in the emitter. The number of emitter electrons clearly increases as p_0 decreases. In an ideal double-barrier diode at 0 K, resonant tunnelling occurs in a voltage range in which the disk moves down from the pole to the equatorial plane of the emitter Fermi sphere. At higher V (when $p_0^2 < 0$) resonant electrons no longer exist, which results in a sharp drop in the current.

Although the basic physical phenomena of resonant tunnelling were previously anticipated, realization of their full potential had to wait until recent improvements in epitaxial techniques. Indeed, materials are now so good that NDR can be readily observed at room temperature (Fig. 1).

Negative differential resistance arises from energy and momentum conservation and from the electron confinement in the quantum-well resonator (Fig. 2). The confinement distinguishes states of motion along the z-direction (perpendicular to the interfaces) inside the well from those outside. Those inside form a ladder of discrete levels, E_0, E_1, . . ., whereas those outside form a continuum of energy states. (The unconfined motion parallel to the interfaces both inside and outside the well, contributing an energy continuum, has only a secondary effect in the process.) Resonant tunnelling into the well occurs only for electrons whose 'forward' kinetic energy in the emitter matches a level in the well (Fig. 2). Biasing effectively lowers the states inside the well relative to the emitter, changing the emitter population that participates in tunnelling.

Tunnelling starts as biasing brings a well level down to the maximum (Fermi) energy E_F of electrons in the emitter. Further biasing increases the number of electrons participating (Fig. 2*c*) so that the conductance increases — the resistance decreases. Eventually, further biasing removes the well level below the minimum energy E_c of conducting electrons and tunnelling ceases. (Imperfections and lattice vibrations at finite temperatures broaden the cut-off and permit a small residual current.) The process is repeated as further biasing brings the next well level down to the Fermi energy.

Biased into one of its NDR regions, the double-barrier diode amplifies oscillations inherent to any resonant circuit with which it is connected. Such spontaneous oscillations often obscure the measurement of the diode's stable current–voltage characteristic. But when mounted in an appropriate cavity, the diode can generate microwaves, wherein lies its main utility. The critical parameter for this use of resonant-tunnelling diodes is the maximum frequency which can be obtained. This frequency is fundamentally limited by the inverse lifetime of electronic states in the quantum-well resonator.

If scattering is not important, the lifetime τ is controlled by the tunnelling processes in and out of the quantum well. In this case, the diode operation is described by the Fabry–Perot picture. For relatively thick barriers (more than 5 nanometers) one can have an extremely sharp resonance (long τ), but this would give a low limit frequency. The double-barrier diodes studied by Whitaker *et al.*[2] were implemented in a GaAs/AlAs heterostructure with extremely narrow barriers (1.5 nanometres), grown by molecular beam epitaxy. The estimated tunnelling lifetime was of the order of one picosecond which translates into a maximum oscillation frequency of about 200 gigahertz. E.R. Brown, W. D. Goodhue and Sollner recently reported[10] measurements of small-signal fundamental oscillations up to this frequency in these diodes.

The large-signal switching experiments reported by Whitaker *et al.*[2] have more in common with the operation of logic elements. The authors performed a real-time measurement by an electro-optic sampling technique, measuring the rise time of switching in a circuit containing the double-barrier diode loaded on a small positive resistor. Because of the NDR characteristic of the diode, such a circuit exhibits bistability in a certain range of the applied bias. If the bias condition changes, the circuit switches. The tricky problem, solved by Whitaker *et al.* (Fig. 3), is to change the bias and sample the circuit response at picosecond speeds. The switching is accomplished in about 2 picoseconds, demonstrating that quantum-well diodes can have a response time comparable to that of fastest all-optical logic elements. Thus these devices could become the basis of future high-speed computers. □

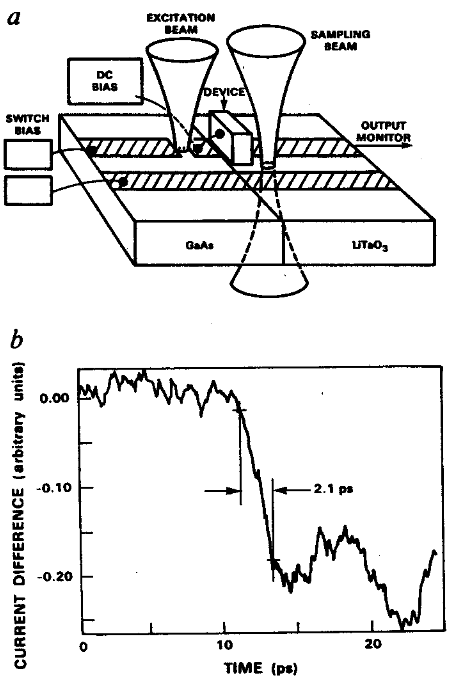

Fig. 3 The experiment of Whitaker *et al.*[2]. *a*, Schematic of apparatus. The optical excitation beam closes a photoconductive switch with an optical pulse lasting only 80 femtoseconds. The sampling beam measures the electric field in the transmission line after the electrical pulse has passed through the resonant-tunnelling diode. The sampling beam is synchronized with the probe beam, so the temporal behaviour of the propagating electrical pulse can be obtained with a resolution of less than a picosecond. *b*, The switching of a resonant-tunnelling diode from its high-current state to its low-current state. The electrical pulse from the excitation beam shown in (*a*) drives the diode above its peak current to a position near the valley current. The circuit allows the bias point to return to its original value so that the next pulse duplicates the action of the previous one. (Courtesy of T.C.L.G. Sollner.)

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