Quantum information storage

Whether energy is necessarily dissipated in computer operations remains an open question. The development of optical computers should help decide the question.

One of the rich but unsettled questions of computer science is how to tell what is the least amount of energy required for the storage of a single binary bit of information in a memory device. There are even some who hold that there may be no lower limit different from zero. For while it is plain that work must be done and energy expended to change the memory state of a macroscopic storage device, say a ferrite core, the amount of energy required is very much a function of the size of the storage devices, which are steadily shrinking in dimensions.

If dreams come true and the dimensions of storage devices are limited only by considerations of quantum mechanics, might not the irreducible energy cost also shrink to zero, at least if it is recognized that energy can be recovered when ordered storage elements are allowed to revert to a random condition?

That is almost certainly an over-facile argument, as is suggested by what is known of the thermodynamics of information storage. Stored information not merely has, but is, negative entropy. Shannon showed that half a century ago, but the analogy between the operation of storage devices and classical thermodynamics can be made much more direct.

The cycle of storing a bit of information and then retrieving it is very like the cycle of operations in an ideal heat engine — the Carnot cycle. The bit is stored, by the expenditure of energy, and then retrieved, whereupon some energy may be recovered. It is readily appreciated that the efficiency of the process will be a function of the temperature, if only because the chance that the stored bit of information will be corrupted, or lost, by random processes in the storage element which are strictly negligible only at absolute zero.

So why not calculate just what amounts of energy are involved for some real device? Hitherto, the impediment has been the analogy in the field of information of the departures from ideality of real-world heat engines. Ferrite cores, being essentially magnets whose direction of magnetization can be changed, are usually outrageously much larger than would be required for the storage of a single bit. The work done in taking them through a cycle may be accurately measured by the area of the usual hysteresis loop, but the quantity thus obtained bears on the size of the ferrite core, not on the energy entailed in storing and retrieving a single bit of information.

That is why there will be much interest in a microscopic information storage device designed (as yet only theoretically) by a group at the University of Stuttgart, G. Obermayer, G. Mahler and H. Haken (*Phys. Rev. Lett.* **58,** 1792; 1987). They start from what is known of the construction of microelectronic devices by epitaxial growth in which layers of difference semiconductors alloys a few Ångstroms thick may be accumulated in a multidecker sandwich. If the electronic properties of the successive layers are suitably chosen, some of them may serve as traps for electrons, or for electron holes, which are the best realizations yet of the classical problem of elementary quantum mechanics, that of a particle in a box (whence the name 'quantum well' structures).

Obermayer *et al.* have worked (on paper) with a three-layer sandwich, one of which is pure gallium arsenide (GaAs) and the other two are alloys of that with different proportions of aluminium. By a suitable choice of the proportions of aluminium, it should be possible to make such a device so that it functions as two separate quantum wells separated physically by a few nanometres. (The calculations are based on a device in which the wells are each 4-nm thick and separated by 16 nm.)

The accessible electronic states in each of the two wells are listed easily enough. First, there are the tightly bound electron states which together are called the valence band, which are ordinarily full, at least in a semiconductor with a finite band-gap. An electron missing from such a state appears as a 'hole', that is as a positively charged entity whose apparent mass is much greater than that of an electron. Then there are the relatively free electron states collectively constituting the conduction band, into which valence electrons may be promoted with increasing temperature, but which otherwise acquire occupants by conduction from elsewhere.

The calculations of the energy states of this system is complicated, and has to be numerical, but it seems clear that each of the wells acts as a trap for electron holes, which are totally confined therein, if for no other reason, because of their great mass relative to that of an electron. The device is therefore one that can store information, as represented by the heavy-electron holes in each well, at least so long as a hole is not filled by the arrival of a stray electron from elsewhere.

In principle, the higher-energy conduction band is therefore the chief means by which information can be communicated from one well to the other, and is thus the means by which holes can be switched from one well to the other. This, of course, has to be accomplished by electron excitation, most simply by light absorption. Obermayer and his colleagues show that it is indeed possible to prepare particular states of the system in a systematic way; suitable potential biasing of the two wells will allow each of them to be driven by light (usually in the infrared) of different frequency. One of the remarkable properties of the general conclusion is that states of the system once prepared are stable at least on the timescale of thermal degradation, while switching speeds may be measured in nanoseconds, all of which is good news for those who hope to use GaAs quantum wells as the elements in optical computers.

The philosophical interest of the system is that, in principle, it makes it possible to consider more completely than has previously been possible the thermodynamics of an information storage device. Obermayer and his colleagues note that many of the muddles of the past have arisen because people have confined themselves to isolated systems, 'closed' in the sense of thermodynamics. Their device, which they figuratively embed in a larger block of GaAlAs, is open (in the same sense) both to electrical influences and because of the interaction of the electron states both with the surrounding radiation bath and with the vibrations of the lattice structure. As a consequence, it should be possible to examine in the detail required the extent of which energy is dissipated in such a device not merely by random interactions with the outside world, but also by the imprecisions of the system for preparing particular storage states.

In an ideal world, it should be possible to set about the measurement of the quantities concerned. The obvious difficulty, made more apparent by these calculations, is that the properties of quantum-well systems are certain to be sensitive to the fine details of their construction. Dimensions will have to be exact, as must be the chemical composition of the several layers of the GaAs sandwich. It remains to be seen how successful these enterprises will be.

John Maddox

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