Vacuum Microelectronics

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Introduction

The last few years have seen references in scientific and economic literature to research and development taking place on “vacuum microelectronics”, but few in the particle physics community seem to know more than these brief, second hand reports, mostly written for a non-scientific readership. The interest of these devices is obvious when it is realised that one of the driving forces for this R. and D. is the military need for electronic components which can withstand very high doses of radiation, which is endemic in experiments involving the new generation of hadron particle accelerators (the SSC in Texas, and the proposed LHC near Geneva). The author therefore arranged to visit one of the centres of research on these components, and the information obtained there formed the principle source material for this summary.

What is Vacuum Microelectronics?

Vacuum microelectronics (abbreviated as VM in this text) is based on the control of electrons in a vacuum by electrostatic and possibly magnetic fields. Only in this respect does it resemble the technology of thermionic vacuum devices, which have now largely been superseded by semiconducting solid state components. In contrast with “valves” (referred to as “tubes” in the U.S.A.), which involved structures between 1 and 10 cm approximately, the “micro” prefix shows that these devices are very small, involving structures measuring only a few micrometres, a scaling down of no less than $10^4$. Their fabrication involves similar techniques to those used in the semiconductor industry. The other major difference is that electrons are not obtained by thermionic emission involving a heated cathode, but by the emission of electrons in an intense electric field (field emission). This is one of the undesirable features of the characteristics of the thermionic valve, which manifested itself as an increase in anode current ($I_a$) with increasing anode volts ($V_a$), normally after saturation of thermal emission had been realised (fig.1). Under these conditions, very high voltages are required to obtain measurable field emission; the aim of VM is to develop high
fields at moderate voltages, relying on the enhancement of the electric field around sharp structures.

Advantages of Vacuum Microelectronics

The primary attraction of VM for applications in particle physics experiments is its extreme resistance to the effects of any kind of ionizing radiation, in view of the high levels of radiation which are expected in the forthcoming generation of accelerators. Since the flow of electrons is through vacuum and not through any matter, there is no danger of damage to the electronic properties of the device. The ultimate limit is presumably when the dose received is such that the structure fails mechanically, or when the flux of radioactive charged particles (of internal or external origin) become sufficient to disrupt the electronic functioning of the device through modifying potentials.

Compared with thermionic vacuum devices, there is a saving in power, heat, and number of connections through the use of field emitting cathodes. The development of these devices depends critically on being able to achieve a rugged, reliable, and long-lived field emitting structure.

The property of small size is obviously essential in achieving competitiveness with modern semiconductor devices. Together with the high mobility of electrons in vacuum and the low capacitance due to the low permittivity of vacuum and small size, this will result in extremely fast devices.

Sources of Information

The principle vehicle for the exchange of information on VM is an annual series of conferences. The last one for which proceedings are presently available (October 1990) was that in Bath, England last year [1]. The third such Conference was held in Monterey, USA in July 1990.

Research Centres

The active research which is known to the author consists of the following. The Stamford Research Institute (SRI) and the Sandia Laboratories, California, USA, are probably the most advanced, other development taking place at the Naval Research Laboratory and elsewhere. There is certainly some activity in Japan, though little seems known about it. In Europe, Thomson-CSF in collaboration with LETI, Grenoble, France, and in England the GEC Hirst Research Centre (HRC) at Wembley and the Thorn-EMI Research Centre in Hayes are known to be active. The research taking place falls into three principal categories: (i) fundamental research, mainly directed at understanding the factors which control field emission; (ii) development of practical cathode structures which satisfies the requirements of high
emission and longevity; and (iii) the identification of the most suitable applications
in terms of devices suitable for fabrication in VM. Although these may be carried out
as separate activities, obviously to a large extent (ii) depends on (i), and (iii) on (ii).
I will now treat each of these areas one at a time.

Fundamental Research

Since the essential and novel aspect of VM devices is the field emitting cathode, un-
derstanding this effect to a level where design and prediction can be carried out is
obviously very important. This is being studied on both a theoretical and experimen-
tal basis [2].

Field emission is basically a tunneling effect as shown in fig. 2. Attempts are being
made to obtain agreement between the calculated field emission and that measured
experimentally. There are some interesting theoretical aspects of this problem; for
example, when the electron is outside the material, it sees an image charge in the
metal which results in electrostatic repulsion, increasing the energy of the electron.
Since the quantum mechanical wave-function which describes the tunneling effect
has a finite value outside the material, the question exists as to the amount this in-
creases the probability of escape of the electron inside the material.

Apart from thinking about such problems as these, on the experimental side the HRC
group is attempting to measure the shape of the surface barrier. It is doing this by
shining light onto the surface of the material; this can be absorbed by an electron in
the conduction band and elevated to an excited state. The probability that this elec-
tron tunnels through the barrier gives some measure of its width (fig. 3).

Cathode Development

As mentioned above, the cathode development programme is aimed at producing
high emission, reproducible, and reliable cathodes. The emission depends of course
on the material forming the surface of the cathode. High emission also implies a
strong field, which is obtained by forming a very sharp structure. The fabrication of
this depends on the material used and the method of forming the point.
Investigations, both theoretical and practical, are being made into the formation of
the pointed cathode by etching and abrasion [1]. Computer models of these processes
are being used in this study.

A typical cathode structure is shown in fig. 4. Approximate dimensions are a few
micrometres, as shown. The radius of the point itself lies in the range 5 to 50 nm, the
smallest being only a few molecules across, hence not resolvable even with an
electron microscope. The "grid" structure near the cathode - in reality a very small hole through which the point of the cathode appears - is to enhance the field at the cathode. Various materials are being tried for fabrication of the cathode structure, included coated structures and liquids [1]. Though the overall basic structure will be fabricated from silicon, as the technology for the manipulation of this material is most advanced, it is not expected to be a good material for the cathode structure. Metals seem to be the most promising candidates. Typically, currents of a few tenths of a microampere are obtained from these structures with potentials of a few hundred volts.

Device Characteristics

Because the probability of an electron tunneling through the surface potential barrier decreases rapidly with increasing width, the electrons emitted all tend to come from the upper energy level in the conduction band. The electron spectrum is thus a fairly tight distribution around the Fermi energy (fig. 5a), in contrast with thermionic devices which show a large spread in electron energy. This results in (fig. 5b) a very steep dependance of anode current on grid voltage ($I_a/V_g$), implying a high amplification factor. The operating point, however, would seem to be difficult to control. It is anticipated that multi-grid structures will be utilised in amplifying or logic devices, in order to stabilise the emission. These extremely small structures can, of course, easily be damaged by too much current flowing, and suitable protection must be arranged. However, it may be that space charge may itself be sufficient to stabilise emission. This may also limit the noise which tends to occur from irregularities in the emission from field effect cathodes.

Device Identification

Apart from military requirements, the most important incentive at the present time is the development of a flat screen television display, which would obviously reduce enormously the bulk, weight, and power consumption of a television receiver. Working prototypes have been demonstrated. Once practical, reliable field emission cathode structures can be fabricated with a good yield, they can be expected to replace thermionic cathodes in conventional macroscopic devices. This will be most useful in situations where power consumption is critical, e.g. for travelling wave tubes in satellites [2]. Obviously longevity is an important criterion in this application. Arrays of at least $10^6$ VM cathodes will be required for macroscopic tubes, but the emission per unit area actually exceeds that of a conventional thermionic emitter.

The first genuine VM devices are almost certain to be digital, since the V/I curve favours this approach, and digital devices are likely to be much more tolerant of changes in emission. Eventually, amplifying devices can be expected. It is these
which are perhaps most interesting for the particle physics community, since the innermost detector system in the experiments on the generation of high intensity accelerators which are just being commenced are in an extremely high radiation environment, and will almost certainly require local amplification. The detectors themselves are somewhat problematic, needle chambers relying on the same micron sized point technology being under development. Gallium-arsenide diode detectors are another possibility, though doubts have been expressed that they are significantly better than silicon detectors.

Conclusion
It is expected that viable cathode structures will be produced within the next two years. Allowing for subsequent device development and production plant to be set up, I would be surprised to see devices on the market in less than five years. Moreover, the first devices will probably not be of interest to particle physics. Thus we can probably assume that these devices are unlikely to be available for the first round of super-collider experiments. However, these experiments will probably not be able to exploit the full intensity capability of the accelerators, and for subsequent generations of experiments these devices could well be the only solution for local (on detector) electronics.

The question then arises whether we can help in the development of these devices. It seems to me that, with only limited resources, a long term time scale, and other commercial incentives for industry, we need not at the moment need to consider participation. The situation might seem different in a few years when the devices are shown to be practicable, and development of types suited to our requirements is necessary.

References
Fig. 1. The effect of field emission on “typical” thermionic valve characteristics.

Fig. 2. Field emission of electrons is by tunnelling through the surface barrier. Electrons emerge with an energy close to the Fermi surface.
Fig. 3. Measurement of the surface barrier shape by photo-excitation of electrons into an excited state, and measuring their probability of escape.

Fig. 4. Typical grid structure and dimensions surrounding a field emission cathode.

Fig. 5 (a) Energy distribution of emitted electrons; (b) $I_a/V_g$ characteristics.