europhysics news

BULLETIN OF THE EUROPEAN PHYSICAL SOCIETY

J.A. Volume 16 Number 7/8 July/August 1985

Localisation & Interaction Effects in Semiconductor Structures

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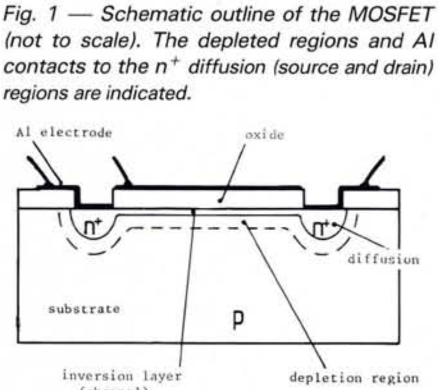
A 1985 Hewlett-Packard Europhysics Prize Winner

The phenomenon of localisation enters into many areas of solid state physics. In this article the use of semiconductor structures for the investigation of localisation and interaction phenomena are discussed.

The silicon MOSFET, in addition to being one of the key devices in microelectronics, has proved to have important applications in solid state physics. The basic structure of the device is illustrated in Fig. 1: the substrate is p type silicon and a layer of silicon dioxide of between 300Å and 1500Å thickness is grown on the surface. Two highly doped n^+ regions (termed the source and drain) are formed by ion implantation and a conducting layer (termed the gate) of either a metal or very highly doped silicon is fabricated on the oxide surface. In the absence of a gate voltage, current will not flow between the source and drain as these regions constitute two back to back p-n junctions. Application of a positive voltage to the gate, with respect to the substrate, drives holes away from the Si-SiO_2 interface and attracts a layer of electrons. This is termed an inversion layer because we have inverted the polarity of the majority carrier at the Si interface. The inversion layer has a low resistance and allows current to flow between source and drain when a voltage is applied between them. The carrier concentration at the Si-SiO_2 interface is changed by simply changing the gate voltage, the specific value being determined by the oxide capacitance.

Fig. 1 — Schematic outline of the MOSFET (not to scale). The depleted regions and Al contacts to the n^+ diffusion (source and drain) regions are indicated.



The inversion layer is extremely narrow, being less than ≅ 80Å and this results in a quantisation of the electron wavefunction in the direction perpendicular to the interface, just as in the case of "the particle in the box". A typical splitting of the quantised energy levels is 20-30 meV. At low temperatures, all carriers are in the ground state and the resultant restriction on momentum normal to the interface results in two dimensional transport because in the plane of the inversion layer a continuum of electron states is available. The attributes of the inversion layer which are useful in solid state physics are the two dimensional transport and the direct control of the carrier concentration, n_{inv}, by the gate voltage. n_{inv} can be varied up to a maximum of $\cong 10^{13}$ cm^{-2} and, hence, any property which depends on carrier concentration, Fermi energy or carrier separation, can be conveniently studied. The system has been used in a wide range of experiments and in this article I shall describe some of the work on localisation and interaction effects.

Charges within the SiO_2 and at the Si-SiO_2 interface give rise to potential fluctuations which localise the first carriers to enter the inversion layer. P.W. Anderson first suggested that in a normal conduction band a random potential would produce localised states. In a conduction band, the electron is free to travel throughout all space, i.e. it is in an extended state. However, when localised, the wavefunction falls off exponentially with distance. The stronger the disorder, the stronger the localisation, with a con-

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Europhysics News is published monthly by the European Physical Society. *ISSN 0531-7479*

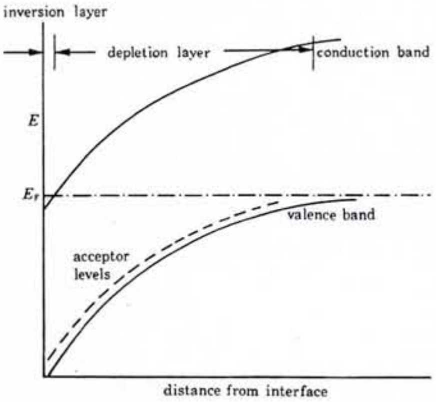
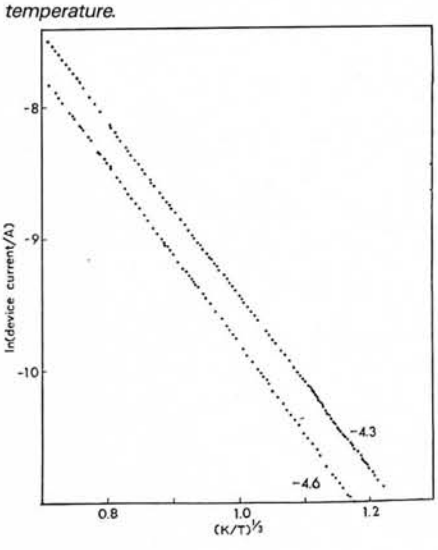


Fig. 2 — The band bending at the p type Si-SiO_2 interface illustrating the formation of the inversion layer and the depletion layer underneath.

sequent decrease in the exponential decay constant.

The localised states act as traps and have to be filled before free electrons can enter extended states in the two dimensional conduction band. When carriers are localised, the process of conduction between source and drain proceeds by electrons jumping from trap to trap. This is a situation which occurs in many disordered systems, and at low temperatures the conduction mechanism is variable range hopping (often called Mott hopping). In this mode of conduction, electrons tunnel to a nearby trap, a process which also requires thermal activation as the unoccupied trap is at a slightly higher energy than the occupied. As the temperature is reduced, the electron tunnels further, in order to minimise the energy required. The conductivity, σ, varies with temperature T as A exp $[-(B/T)^{1/3}]$ where A and B are constants. (In three dimensions the extra degree of freedom for electron hops changes the 1/3 power to 1/4.) An example of this behaviour is shown in Fig. 3.

Fig. 3 — Two examples of variable range hopping in the silicon inversion layer for two similar values of gate voltage. Log conductivity is linear against $(K/T)^{1/3}$ where K is a constant with dimensions of temperature.



Increasing the number of carriers by increasing the gate voltage of the device moves the Fermi energy E_F through the localised states. (The Fermi energy is approximately the energy of the highest occupied electron state in the system.) As E_F increases, the gradient of the $T^{1/3}$ plot decreases, until eventually this temperature dependence is lost.

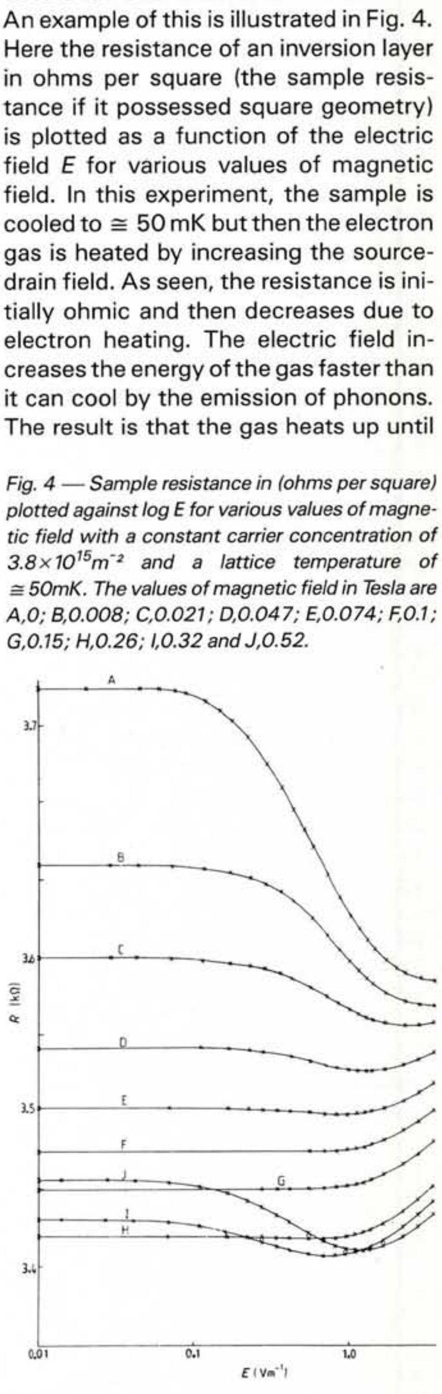
At higher temperatures, conduction proceeds by a process of excitation of electrons to those extended states in which an electron is able to propagate throughout the specimen. In three dimensions, it was first suggested by Sir Nevill Mott that a sharp edge, the mobility edge, separates extended and Anderson localised states. For two dimensions, recent theoretical work — Abrahams, Anderson, Ramakrishnan and Licciardello, Kaveh and Mott, Bergmann, Haydock and many others [1]) — has shown that extended states do not exist. However, at finite temperatures the very large localised states cannot be observed as an electron is scattered into another state before diffusing the localisation length. This process of inelastic scattering effectively cuts off the localisation and gives the impression that extended states exist.

One of the most interesting current topics in two dimensional transport is quantum interference. This produces the now well-known "logarithmic corrections" to the conductivity. The phenomenon occurs when $k_F\ell > 1$ (k_F is the Fermi wavevector and ℓ is the elastic (impurity) scattering mean free path) and results in a conductivity correction $S_\sigma \sim \ell n\,(L/\ell)$ where L is the inelastic diffusion length. Since L varies with temperature T as T^{-x}, the correction becomes $S_\sigma \sim \ell n T$ which has been observed in many systems. Physically this effect arises because an electron can be elastically scattered around in a loop. Interference occurs between electron waves which traverse the loop in the two opposing directions, with as net result a decrease in the conductivity. Application of a magnetic field transverse to the plane of the electron gas suppresses the interference by changing the phase of the waves and gives rise to a negative magneto-resistance, which, at low temperatures, can be noticeable at fields as small as 50 G.

Another mechanism which gives rise to a logarithmic correction is the electron-electron interaction, a suggestion originally due to Altshuler and Aronov. They pointed out that the combination of impurity scattering and the electron-electron interaction modifies the density of states at the Fermi energy $N(E_F)$. In 2D this causes a minimum at $N(E_F)$ and a logarithmic correction in the conductivity, i.e. the same temperature dependence as the quantum interference.

It can be difficult to distinguish between these two logarithmic corrections and initially it was not clear which was appropriate. However, in the silicon inversion layer the magnitude of the interaction correction is reduced owing to electron screening. The application of a magnetic field reduces the role of the screening, and, correspondingly, the interaction correction is enhanced. In these circumstances a magnetic field can be used to separate the quantum interference and interaction corrections. An example of this is illustrated in Fig. 4. Here the resistance of an inversion layer in ohms per square (the sample resistance if it possessed square geometry) is plotted as a function of the electric field E for various values of magnetic field. In this experiment, the sample is cooled to $\cong$ 50 mK but then the electron gas is heated by increasing the source-drain field. As seen, the resistance is initially ohmic and then decreases due to electron heating. The electric field increases the energy of the gas faster than it can cool by the emission of phonons. The result is that the gas heats up until

Fig. 4 — Sample resistance in (ohms per square) plotted against log E for various values of magnetic field with a constant carrier concentration of $3.8 \times 10^{15} m^{-2}$ and a lattice temperature of $\cong$ 50mK. The values of magnetic field in Tesla are A,0; B,0.008; C,0.021; D,0.047; E,0.074; F,0.1; G,0.15; H,0.26; I,0.32 and J,0.52.



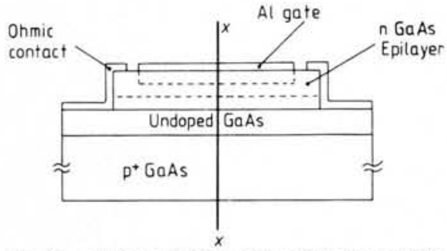


Fig. 5 — Schematic illustration of the GaAs FET; the expitaxial layer to be investigated is deposited on an undoped layer on a p^+ substrate, then a Schottky gate and ohmic contacts are formed.

the rate of energy loss, balances the energy input; for the range of fields used the electrons heat to about 1K.

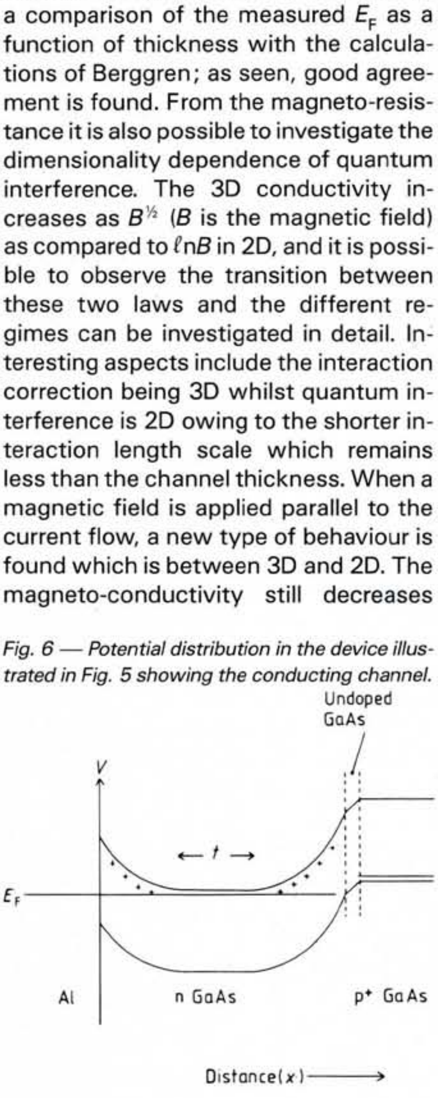
As seen from Fig. 4, increasing the magnetic field results in a negative magneto-resistance and a suppression of the temperature dependence of the resistance. When the magnetic field increases above the value required to induce the interaction mechanism, the magneto-resistance becomes positive and a logarithmic correction returns. It can be observed that as the electron temperature increases, the magneto-resistance changes from positive to negative, indicating that the two mechanisms are present together, and the removal of the interaction effect allows the observation of the interference. It is only when the magnetic field is sufficiently strong for the electrons to describe complete orbits in space that the interference is removed. Differences between the interaction and localisation corrections have been found in the Hall effect. (This work is discussed in detail in reference 1.)

Analysis of the negative magneto-resistance arising from the suppression of the quantum interference allows investigation of the distance an electron diffuses before being inelastically scattered into another state. The interference process is cut off by this scattering which causes a change in the wavelength of the electron. The results of such an analysis indicate that the presence of disorder introduces an indeterminacy in the electron momentum. This relaxes the requirement of conservation of momentum in electron-electron scattering and a faster scattering rate occurs. The existence of these temperature dependent corrections also allows the electron gas to be used as its own thermometer. The emission of phonons by hot electrons can now be investigated and it is found that disorder also introduces a more rapid rate of phonon emission.

Another type of structure which has proved to be useful in the investigation of localisation is the GaAs Schottky gate FET. This type of device is depicted in Fig. 5 and the potential distribution is shown in Fig. 6. By making the gate voltage more negative, the thickness of the conducting channel can be reduced. Initially the reduction in thickness merely produces a thinner 3D sample but eventually the thickness becomes sufficiently small that the confinement produces quantised levels. The formation of sub-bands results in transport becoming 2D as in the inversion layer.

One method of investigating this dimensionality transition is to measure the change of Fermi energy, E_F; a very convenient way of accomplishing this is by measuring the Shubnikov-de Haas oscillations. These oscillations of resistance occur in the presence of a transverse magnetic field sufficiently large that the density of electron states as a function of energy has peaks due to the formation of electron orbits. A simple formula relates the periodicity of the oscillations and Fermi energy, and it is found that E_F decreases from the 3D value when the thickness becomes less than ≅ 1000Å (precise value depends on doping) and the number of quantised sub-bands below E_F becomes few. (Reference 2 discusses this work in detail.) Fig. 7 shows a comparison of the measured E_F as a function of thickness with the calculations of Berggren; as seen, good agreement is found. From the magneto-resistance it is also possible to investigate the dimensionality dependence of quantum interference. The 3D conductivity increases as $B^{1/2}$ (B is the magnetic field) as compared to $\ell n B$ in 2D, and it is possible to observe the transition between these two laws and the different regimes can be investigated in detail. Interesting aspects include the interaction correction being 3D whilst quantum interference is 2D owing to the shorter interaction length scale which remains less than the channel thickness. When a magnetic field is applied parallel to the current flow, a new type of behaviour is found which is between 3D and 2D. The magneto-conductivity still decreases with temperature as $\ell n\, T$ in the 2D manner but increases as $B^{1/2}$ in the 3D manner. This variation of the different length scales enables the richness of the quantum corrections to be brought out, including the dimensionality dependence of electron-electron and electron-phonon scattering. Another feature of this structure which is particularly useful, is that as with most semiconductors, the transition to strong localisation can be induced by the application of a strong transverse magnetic field. By varying the thickness of the conducting channel, this transition can be investigated in both 3D and 2D.

Fig. 6 — Potential distribution in the device illustrated in Fig. 5 showing the conducting channel.



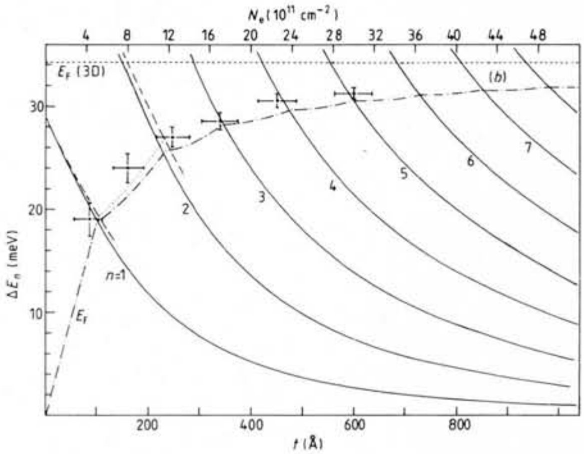


Fig. 7 — The variation of E_F with thickness (and sheet carrier concentration) for a Schottky gate FET of doping $5\times10^{17}cm^{-3}$. The sub-band quantisation is shown, the solid lines indicate the sub-bands calculated by Berggren with a WKB method and the broken curves are calculated by a variational method. The 3D E_F is indicated and the experimental values are the circles with error bars attached.

A striking phenomenon which is caused by localisation is the Quantum Hall Effect. Here a plateau of quantised Hall resistance is found when E_F is in localised states in the Landau levels; often the localisation is only apparent at quite low temperatures. The localisation lengths are long so that if the inversion layer current is driven at a finite frequency, then electrons have the possibility of responding to the frequency within a localised state. An example of this effect is shown in Fig. 8, which (like other results on this effect) was found in a collaborative project with H. Myron and his group at the University of Nijmegen high magnetic field laboratory. Results with the 2D electron gas in GaAs-AlGaAs heterojunctions show a different frequency dependence, indicating that it may be a useful diagnostic technique for the investigation of disorder in these structures. When the quantised Hall plateau is removed by frequency then fractional quantisation becomes apparent. Here the action of the frequency in minimising the role of the disorder is enhancing the electron-electron interaction to give the same effect as much higher mobility samples under DC conditions [3].

Developments in semiconductor technology offer the prospect of new types of structure and materials which will extend the scope of experimentation. If past experience is a guide [4]), there will be new and exciting phenomena waiting to be found in addition to those known at the present time.

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Fig. 8 — The frequency dependence of the quantised current in the i = 4 step is illustrated. The device is 400μm long by 50μm, the magnetic field is 8 T and the temperature is 1.2K.