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DIELECTRIC SPECTROSCOPY OF SEMICONDUCTORS

3<sup>rd</sup> Progress Report to July 1988  
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ABSTRACT

Dielectric response measurements are reported on three types of devices, two of them junction diodes on high-resistivity silicon and the third a Metal/Oxide Field Effect Transistor (FET) in nearly cut-off condition. The two diodes, despite similarity of their structures, show significant differences in their delay and transition rates, as manifested by their dielectric responses. The FET work is confirming a theoretical prediction that a two-dimensional electron gas should show strongly dispersive behaviour. *semiconductors. (figure)*

INTRODUCTION

In the first Progress Report by A K Jonscher and M N Robinson we have given a detailed account of the results obtained using our technique of Dielectric Spectroscopy of Semiconductors on p-n junctions and Schottky diodes on high and medium resistivity silicon. These results have shown a number of features which clearly distinguish barrier devices containing interfacial states, such as Schottky diodes, and those which do not, such as p-n junctions. The material covered in that report which has since been published [1] complements in a very significant way the results obtained in our Group in the past on a wide range of p-n junctions, and this has contributed to the development of a new approach to the interpretation of the dielectric response of semiconductors in general, and of barrier devices in particular. This has appeared as our 2<sup>nd</sup> Progress Report for December 1987.

In the current reporting period we return to experimental work which concerns two very different types of devices:

- PIN diodes on very high-resistivity silicon;
- a diffused diode on high-resistivity silicon, and
- the drain-source current in Insulated Gate Field Effect Transistors (FETs).

The PIN diode, kindly supplied by Martin Marietta Research Laboratories in Orlando FL, has silicon base resistivity of  $10^4 \Omega\text{cm}$  with a Boron doped  $p^+$  area on the light-incident side, and a Phosphorus doped diffused layer at the back. Our motivation in studying this device was that it represents the highest resistivity base material in our experience and it also shows a very high photosensitivity. In addition, we would like to study the precise time dependence of the

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decay of its open-circuit photovoltage which persists at room temperature for the remarkably long time of several milliseconds in the main decay process and for much longer in the following "tail". Facilities for a detailed study of the photovoltage are only now becoming available and this should appear in our next Progress Report, although we have already noticed some interesting features in the time dependence of the photodecay..

The diffused diode on 3,000  $\Omega$ cm silicon, kindly supplied by Mr D H J Totterdell of the UK Atomic Energy Authority at Harwell, represents in many ways a similar type of device to the PIN Diode.

Our approach to the measurements of the source-drain currents in FETs is based on the notion that the channel region in these devices constitutes a good approximation of a two-dimensional electron gas (2-DEG) and as such has been the subject of a wide range of studies of electrical and galvano-magnetic properties which exhibit wholly unexpected features. While all these have been concerned substantially with direct-current (dc) responses, or at most with single-frequency behaviour, we became interested in the wider frequency range response of the nearly-cut-off channel. The reason for this is based on our wide-ranging experience with charge transport in low-dimensional systems, mostly ionic ones, such as humid insulators in which there is clear evidence of filamentary flow, coupled with the presence of Low-Frequency Dispersion (LFD) of the real and imaginary components of the effective capacitance [2,3]. We felt that it would be very interesting to check if similar LFD processes can be seen in the purely electronic system of a FET channel.

#### ***PIN diode on high-resistivity silicon***

This device shows an interesting behaviour which is given in Figure 1 as a series of spectra on the same axes, without any attempt at normalisation, since the character of the response is changing with temperature, indicating the onset of new processes, rather than simply a change in the characteristic rates of the same process. The lowest temperature data shown, corresponding to 90K, do not differ from those obtained at 150K which are not reproduced here, suggesting that there is an irreducible low-temperature process which is dominated by direct current (dc) conduction. With increasing temperatures above 200K there is a progressive development, in addition to dc conduction, of some loss process which is not normalisable and which becomes dominant over a wide range of frequencies at 300K.

The high-frequency rise of loss is compatible with a series resistance of 3,000  $\Omega$  which would be consistent with the known parameters of the diode and also with the measured dc current - voltage characteristic, which clearly shows a dominance by that value of series resistance.

#### ***Diffused Diode on high-resistivity silicon***

Although this device appears to be in many respects structurally similar to the PIN diode described above, its dielectric spectrum shows considerable differences, in that there is but one single strongly dominant feature in the entire temperature range 85 - 200 K. The normalised spectrum of this diode is shown in Figure 2, together with the locus of normalisation, from which the temperature dependence of the peak frequency can be determined.

The loss peak has an activation energy of 0.27 eV at temperatures in excess of 120K. Its

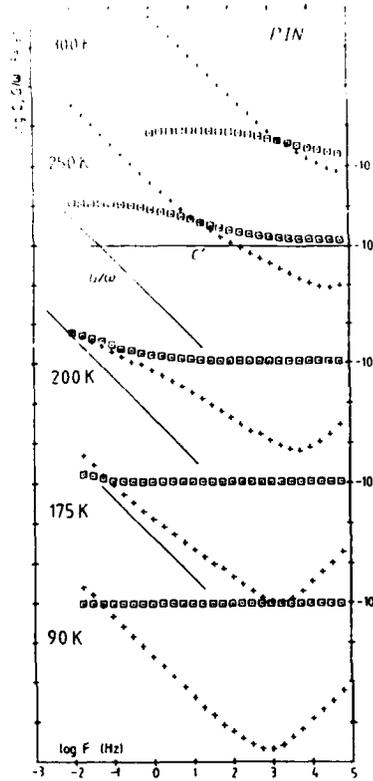


Figure 1. The dielectric response of the PIN diode on 10,000  $\Omega\text{cm}$  silicon shown as a series of spectra for temperatures in the range 90 - 300 K. No attempt has been made to normalise these spectra, since their character changes with rising temperature, indicating the onset of new processes, rather than simply the changes of rates of the same processes. However, to facilitate orientation in the relative positions of the various data, the contours of  $G(\omega)/\omega$  at 90K have been indicated on the higher-temperature data (except 300K) and  $C'(\omega)$  has been indicated on the 250K data.

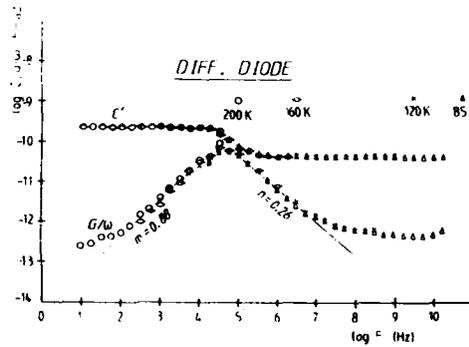


Figure 2. The normalised frequency response of the diffused diode on 3,000  $\Omega\text{cm}$  silicon, showing a single dielectric loss process corresponding to a slightly broader-than-Debye response with the power-law exponents  $n = 0.22$  and  $m = 0.89$  (Debye would have been  $n = 0$  and  $m = 1$ ). The activation energy of the loss peak is 0.27 eV below 200K.

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shape deviates significantly from the Debye spectrum, indicating deviation from the classically expected exponential time dependence. This loss peak has a considerable magnitude, giving rise to a nearly ten-fold dispersion of  $C''(\omega)$ , indicating a high density of centres responsible for it. The deviation from Debye shape suggests strongly that the processes involved is not series resistance effect, as in the case the PIN diode.

### *FET in nearly cut-off condition*

#### *Experimental Results*

We have made measurements on two types of commercially available FETs, a low-power low-noise Type 2N4220 of 300 mW and a medium-power switching FET Type 2N4092 of 1.8 W.

When the gate-source bias,  $V_{GS}$  is set so that the FET is in its strongly conducting state, the drain-source current  $i_{DS}$  shows true dc response, i.e. the drain-source conductance  $G_{DS}$  is independent of frequency in the range under investigation. This means that the transport of carriers in the channel responds instantaneously to any variations of the drain-source voltage  $V_{DS}$  as would be expected in this type of device. This is clearly seen in our measurements, except that the highest values of  $G_{DS}$  fall outside the range of our measuring equipment so the tests of frequency dependence have to be made in the intermediate range. Also, it is impossible to determine the capacitance  $C'$  against the high conductance background. When  $V_{GS}$  bias is set to cut off the channel flow, the device behaves as a lossy dielectric, with a low dielectric loss  $C''(\omega) = G_{DS}(\omega)/\omega$  which is fairly independent of frequency, implying that  $G_{DS}(\omega)$  is a sharply rising function of  $\omega$ . The capacitive component  $C'(\omega)$  is independent of frequency and it probably corresponds to stray capacitance in the system.

The behaviour expected by us sets in at a critical value of  $V_{GS}$  corresponding to the onset of channel conduction and is shown in Figure 3. While the behaviour of  $G(\omega)$  at high frequencies is little affected, a clear break is seen at a lower frequency value below which  $G(\omega)$  becomes *almost but not quite constant*, and there is a corresponding increase of  $C'(\omega)$  towards low frequencies.

The behaviour of the medium-power FET is not the same - the lower-frequency branch of  $G(\omega)$  still shows a distinct difference from higher-frequency branch, but its dependence on  $\omega$  corresponds to larger values of  $n_s$ , and the dispersion of  $C'(\omega)$  is correspondingly stronger. At the present time we do not yet understand the reasons for these differences in behaviour - they may well be connected with different geometries of the two devices, since we have learnt in our earlier work that this has a strong influence on the LFD behaviour.

One significant feature has become evident in the course of our FET measurement - they reveal a definite instability of the FET channel conduction at low frequencies, which causes the results to appear erratic in certain frequency ranges and often leads to the appearance of spurious negative capacitances or conductances. For some time we have been blaming our new computerised FRA for these artefacts, but careful checks have shown that these anomalies are associated with our samples. Somewhat similar conclusions were reached when we attempted to measure the response of our FET samples at lower temperatures - typically at 77K - despite the fact that  $V_{GS}$  was adjusted to bring the conductance back to similar values as at room tem-

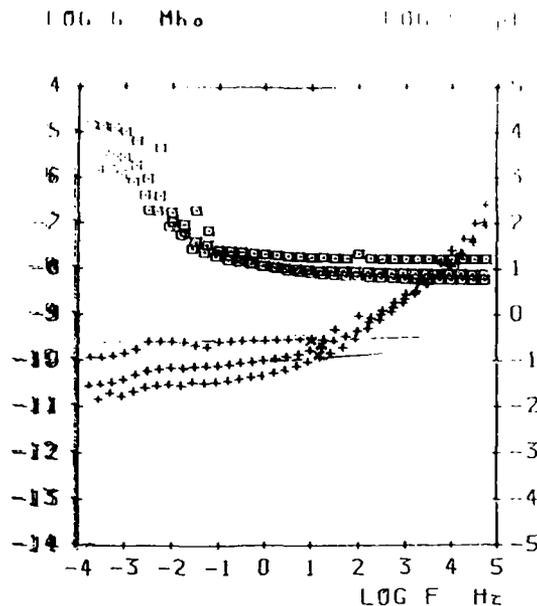


Figure 3. The dielectric response of a MOSFET in nearly cut-off conditions, shown as plots of  $\log G(\omega)$  (crosses) and  $\log C'(\omega)$  (squares) against  $\log(\omega/2\pi)$ , for three values of gate-source bias  $V_{GS}$ . The low-frequency data for  $G(\omega)$  show small but unmistakable slopes corresponding to LFD behaviour and this is borne out by the strong dispersion of  $C'(\omega)$ .

perature. The data from the computer became completely erratic and an attempt to measure the parameters manually on our General Radio bridge resulted in a complete failure to obtain any significant data. While these may be early days for the pronouncement of any definitive verdicts on the significance of these results, we propose to comment on them in the following Section.

### Conclusions

The experimental data on high-resistivity silicon diodes suggest that significant differences may be seen between the dielectric responses of devices having nominally similar structures. This proves the value of our type of measurements in assessing semiconductor devices. We are at present unable to identify the specific features of the dielectric behaviour with any definite structural or impurity features in these devices, although it may become possible to do so in collaboration with the suppliers. It is evident that the different processes through which these devices had been taken have resulted in very different transition rate processes giving the characteristic spectra shown.

The FET work opens up a new line of study of some fundamental significance, which does not appear to have been investigated at all. Although it is too early to pronounce definitively on the results obtained so far, it appears reasonable to suggest that the prediction of strongly dispersive properties of filamentary flow in a two-dimensional electron gas has been tentatively borne out.

**Acknowledgements**

It is a pleasure to acknowledge the supply of devices for testing by Mr ... of Martin Marietta Research Laboratories in Orlando FL and by Mr D H J Totterdell of the UK Atomic Energy Authority at Harwell.

**References**

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