AC profiling by Schottky gated cloverleaf

amplitude fluctuations in that frequency go out of the instrument range. Thus in a real flow the system can be used in regions of large scale and intensity of turbulence with little effect upon the high frequency part of the spectrum, other than lowering its absolute level. This last point is believed to be correctable by an additional element in the tracking filter.

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AC profiling by Schottky gated cloverleaf

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Abstract Depletion type profiling methods offer clear advantages over stripping techniques provided that depletion of the region of interest can be attained without the surface field exceeding the critical value for the material under test. Two well known methods are (i) differential CV measurements by which $n(x)$ may be determined with a high degree of accuracy, and (ii) stepwise depletion from a Schottky or MOS gate suitably located in a sample in Hall geometry by which $n(x)$ and $\mu(x)$ can be measured less accurately. This paper outlines a method combining virtues of both approaches in which the stepped DC applied to the Schottky gate on a van der Pauw cloverleaf is modulated by an AC signal and AC components of Hall and van der Pauw voltages are synchronously detected. Equations governing the extraction of $\mu(x)$ and $n(x)$ from the data are given and two sample experimental results presented.

1 Introduction

Total impurity content data is insufficient for the characterization of many semiconductor devices unless its spatial distribution is also known. This is especially true of thin layer structures, such as Gunn diodes and microwave transistors, for which successful modelling is critically dependent on carrier concentration (n) and mobility (μ) as a function of depth. The most commonly used profiling methods are chemical stripping (Schmidt and Michel 1957, Johansson *et al.* 1970) in which some reaction allows a uniform known thickness of sample to be removed, a comparison being made between the electrical properties before and after, and depletion in which the electrical contribution of a known layer is removed by depleting that layer of free carriers. Anodization and HF removal of oxide and, recently, sputter etching (Cahen and Netange 1970, Davidson 1971) are popular versions of the former approach, whilst depletion under an MOS gate (Elliot and Anderson 1972, Ipri 1972) has been used for the latter. Information on the depth variation of both parameters of interest is easily derived as the van der Pauw (1958) measurement gives the conductivity–thickness product of the wafer in the well known form

$$\sigma d = \frac{2 \ln 2}{\pi} (R_1 + R_2)^{-1} f^{-1}(R_1, R_2) \tag{1}$$

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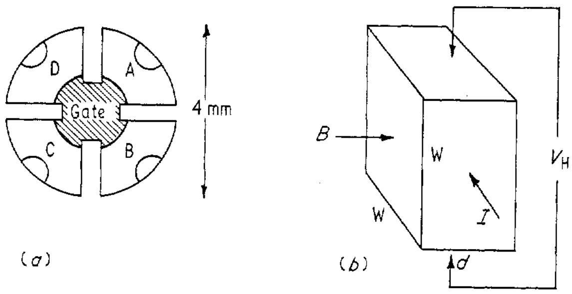

Figure 1 Schematic diagram of (*a*) sample geometry and (*b*) dimensions of active area

where, referring to figure 1, the resistances R_1 and R_2 are given by measuring the ratios V_{CD}/I_{AB} and V_{DA}/I_{BC}, respectively and f is a known function of R_1/R_2. Conveniently for a set of i adjacent layers

$$\sigma d = \sum \sigma_i d_i \tag{2}$$

so that if the mth layer can be removed, its departure is reflected in the change in the value of σd for the whole sample

$$\sigma_m d_m = \Delta[\sigma d]_m = \frac{2 \ln 2}{\pi} \Delta[(R_1 + R_2)^{-1} f^{-1}]_m. \tag{3}$$

Meanwhile the Hall coefficients, R_i, for the same set of layers are additive as (see for example Clark and Manchester 1968)

$$R\sigma^2 d = \sum R_i d_i \sigma_i^2 \tag{4}$$

so the change effected by the removal of the mth layer is, as above, related to the properties of that layer as

$$R_m \sigma_m^2 d_m = \Delta[R\sigma^2 d]_m. \tag{5}$$

For the sample geometry of figure 1, equations (3) and (5) can be combined to give

$$R_n(\Delta\sigma d)^2/d_n = \Delta[V_H(\sigma d)^2]/IB \tag{6}$$

then the carrier concentration and Hall mobility in the removed layer are given by

$$n_n = [\Delta(\sigma d)]^2 IB/\Delta[V_H(\sigma d)^2] q d_n \tag{7}$$

and

$$\mu_n = \Delta[V_H(\sigma d)^2]/IB\Delta[\sigma d]. \tag{8}$$

Thus by repeated Hall–van der Pauw measurements for a sample in, for example, clover leaf geometry, the variation of R and σ, and hence μ and n with depth may be elucidated.

Clearly stepped methods, etch or depletion, have a disadvantage in that the desired parameters appear as small differences between large values. This may render the method unworkable when profiling, for example, a thin n layer on an n^+ substrate. In such cases a capacitance technique may be usable, though confined to arrangements in which the maximum field (surface field for a Schottky barrier, interface field for a p–n junction) is below the critical field beyond which breakdown occurs. This limits the exposable ionized impurity density to about $2{\cdot}5 \times 10^{12}\ \mathrm{cm^{-2}}$ of surface area for n Si, corresponding to a depth of 10 μm for 2 Ω cm (e.g. collector) doping but only 100 Å for $10^{-2}\ \Omega$ cm (e.g. emitter) levels. In spite of this restriction the use of AC capacitance as the measurement tool means that n can be determined with high accuracy at the depletion region edge at the point of measurement and by stepping the DC bias a precise doping profile can be obtained although, of course, the concomitant mobility profile is not available. A method of combining the AC depletion profiling and van der Pauw measurements to provide this additional information with the same accuracy is given in the following section.

2 Measurement

In this method we use a clover leaf sample with a Schottky-barrier gate covering its central active region and apply a fixed reverse bias to predetermine the depth of the layer which is to be measured. A thin layer of material at the edge of this DC depleted region is then characterized by superimposing an AC signal at the gate and synchronously detecting the depth of modulation on van der Pauw and Hall signals.

Setting $I_{AB} = I_{BC} = I$ we have from equation (3)

$$\Delta[\sigma d] = \frac{2I \ln 2}{\pi f} \Delta \left[\frac{1}{V_{CD} + V_{DA}}\right]. \tag{9}$$

It may readily be shown that f can be treated as a constant whilst $0{\cdot}5 < R_1/R_2 < 2$ as is highly likely in practice. Setting a modulation depth small in comparison with background values, equation (9) expands to

$$\Delta[\sigma d] = \frac{2I \ln 2}{\pi f} \left(\frac{\Delta V_{CD} + \Delta V_{DA}}{(V_{CD} + V_{DA})^2}\right). \tag{10}$$

Similarly expanding equations (7) and (8) and substituting for $\Delta[\sigma d]$ from equation (10) gives

$$n_n = \frac{IB}{q d_n} \left(\frac{t^2}{\Delta V_H - 2tV_H}\right) \tag{11}$$

and

$$\mu_n = \frac{2 \ln 2}{\pi f B} \left(\frac{\Delta V_H - 2tV_H}{\Delta V_{CD} + \Delta V_{DA}}\right) \tag{12}$$

where

$$t = \left(\frac{\Delta V_{CD} + \Delta V_{DA}}{V_{CD} + V_{DA}}\right).$$

These equations then give the local μ and n in terms of the modulation in van der Pauw and Hall voltages ΔV_{CD}, ΔV_{DA} and ΔV_H using their background DC values V_{CD}, V_{DA} and V_H as calibration terms. The layer under examination at DC bias V_A is located at depth d from the surface given by the simple voltage capacitance relationship $d(V_A) = K\epsilon_0 A/C$ in the usual nomenclature.

For convenience if A is the Schottky barrier area ($\mathrm{mm^2}$) and C its capacitance (pF)

$$d = 106{\cdot}1 A/C\ \mu\mathrm{m}\ \text{for GaAs} \quad \text{and} \quad d = 103{\cdot}6 A/C\ \mu\mathrm{m}\ \text{for Si}. \tag{13}$$

The method is primarily useful in profiling for mobility (*via* equation 12) but extraction of d_n from the C–V measurement allows n profiling (*via* equation 11) since

$$d_n = \Delta V_A K \epsilon_0 \Delta C^{-1}/\Delta V_A. \tag{14}$$

3 Experimental

Cloverleaf samples were prepared by airbrasion and given small ohmic edge contacts of Au–4% Sb for n Si or Ag–4% Sn for n GaAs of Gunn diode doping. Gold provided the rectifying gate contact to either material. The contacted sample was mounted in a light tight box in such a way as to allow insertion into the gap of either an electromagnet or, quite conveniently, a magnetron horseshoe. Gold plated molybdenum facsimiles of DIL leadframes were made for this use since standard frames and headers are invariably ferrous metal based and thus unsuitable for Hall measurements.

A block diagram of the measuring circuit is given in figure 2, which shows the arrangement for measuring Hall voltage. The contact permutations for van der Pauw measurement, current

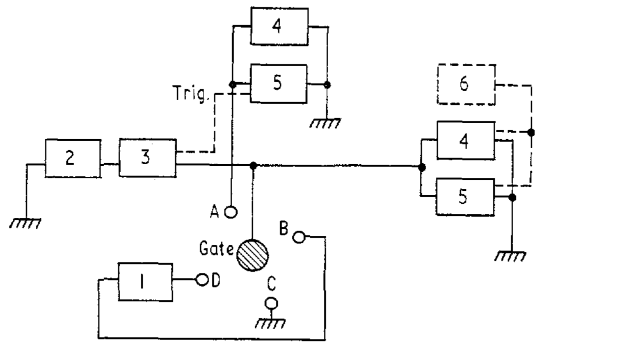

Figure 2 Experimental arrangement for gated Hall–van der Pauw measurements. 1, current source; 2, DC volts; 3, AC volts; 4, DC electrometer; 5, lockin amplifier; 6, digital display

reversal etc., are obvious and are effected in practice by a simple switchbox.

The gate is biased by a DC source determining the average depletion depth and modulated by an oscillator, the output of which determines both sensitivity and resolution. The Hall or van der Pauw voltage is analysed by a parallel arrangement of DC electrometer, of sufficiently slow response to ignore the modulation, and lockin amplifier triggered from the bias oscillator. The three voltages of interest and their respective depths of modulation are read directly by this means, and the same pair provides a check on the actual values of gate bias. Measurement then proceeds as standard for a range of depletion depths, μ and n are calculated at each and the sequence ends with a capacitance voltage run for depletion depth and d_n calibration *via* equations (13) and (14).

4 Results and discussion

Examples of concentration and mobility profiles for an n Si epilayer and an n GaAs Gunn diode layer, each approximately 5 μm thick are given in figure 3. A 50 mV gate modulation was

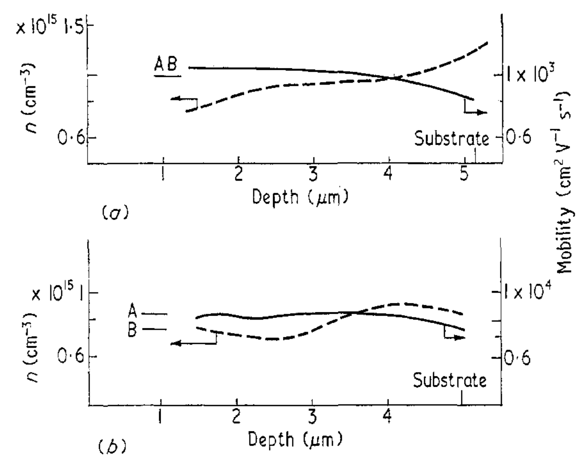

Figure 3 Mobility and carrier concentration profiles of two samples. (*a*) n Si on n$^+$ substrate, (*b*) n GaAs Gunn diode layer on n$^+$ substrate. A and B are layer-average values of mobility and concentration measured conventionally

used for both samples giving a depth resolution of approximately 0·03 μm. In each case the conventionally measured average values for the whole layer are also given and seem to be in good agreement with the profiled values.

As remarked earlier, profiles may be determined with considerably greater accuracy than by step methods, the improvement depending upon the sample material. This is because the method of finding a relatively small difference between two quantities is replaced by electronic extraction of the information by phase sensitive detection of the magnitude of the signal generated by oscillation between them. Thus the actual magnitude of background values is not important. This can be illustrated as follows: suppose 0·03 μm resolution (as above) is required through a 6 μm layer and 5% error in n is acceptable; by the present method this is readily obtainable *via* equation (11) by 1% meter readings. For stepwise (equation (7)) measurement, however, a total accuracy of 0·01% in all readings is required as the values of Hall and van der Pauw voltages before and after the step will differ only by something like the ratio 0·03 μm : 6 μm, i.e. 1 : 200. In practice an averaging over several successive steps can be used with a loss of resolution commensurate with the gain in accuracy. For the cited examples the statistical fluctuation in repeating points was about 5%. Identically processed samples from the Si slice used showed reproducibility within this error providing sufficient care was taken in resetting the bias conditions.

Replacement of the phase sensitive detector by straightforward capacitive decoupling of the DC signal with or without narrow bandpass filtering centred at the measuring frequency was thwarted by the intrusion of instrument noise into the low-level (millivolt) AC component. No attempt to optimize this variation of the method was undertaken given the availability of efficient electronic extraction.

5 Concluding remarks

This note describes an improved technique for profiling carrier concentration and mobility in semiconductor samples.

The gated Hall method introduces the accuracy associated with C–V measurements to the determination of mobility profiles, but has similar limitations in the depth measurable in higher doped materials. This, however, is not a disadvantage in some applications, notably the characterization of thin epilayers on higher doped isotype substrates.

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