A METHOD TO OVERCOME THE PROBLEM OF SERIES RESISTANCE IN THE CAPACITANCE-VOLTAGE TECHNIQUE FOR CARRIER DENSITY DETERMINATION

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The net donor density of n type GaAs epitaxial layers is commonly determined from capacitance-voltage measurements made on a Schottky barrier deposited on the epitaxial layer. The back ohmic contact is usually alloyed to the substrate, if it is n type, or to the layer itself, if the substrate is semi-insulating (Fig. 1). In the latter case, the resistance $R$ in series with the Schottky diode capacitance $C$ can be significant and can introduce an error in the determination of $C$. In this note, a practical solution to the problem is proposed.

The capacitance meter used for C-V characterization usually measures capacitance by phase sensitive detection. Under conditions of constant bias, the a.c. equivalent circuit between the Schottky and ohmic contacts consists of a capacitance $C$ in parallel with a leakage a.c. conductance $G$, this combination being in series with the resistance $R$ (Fig. 2). The admittance $Y$ between the ohmic and the Schottky contacts at $\omega/2\pi$ hertz can be expressed as

$$Y = G' + j\omega C'$$

(1)

where $\omega$
\[
G' = \frac{[GH + \omega^2 RC^2]}{[H^2 + \omega^2 R^2 C^2]},
\]

and
\[
C' = \frac{C}{[H^2 + \omega^2 R^2 C^2]},
\]

and where
\[
H = RG + 1.
\]

A small signal a.c. voltage \( \vec{V} = V_0 e^{j\omega t} \) (typically 15 mV at 1 MHz) is superimposed on the d.c. bias. By detecting the current 90° out of phase with \( \vec{V} \), the capacitance meter essentially measures \( C' \). For Schottky barriers on GaAs, \( G \) is usually very small. Under the conditions \( RG \ll 1 \) and \( \omega^2 RC^2 \gg G \), Eqs. (2) and (3) become
\[
G' = \frac{\omega^2 RC^2}{1 + \omega^2 R^2 C^2},
\]

and
\[
C' = \frac{C}{1 + \omega^2 R^2 C^2}.
\]

For high purity (n\textsuperscript{-}) GaAs layers about 10 microns thick, doped in the low \( 10^{14} \text{ cm}^{-3} \) range, and grown on semi-insulating substrates, the sheet resistance can be of the order of \( 10^4 \text{ ohms/} \square \). For 0.030" diameter Schottky barrier contacts, the zero bias capacitance is typically in the range 10 - 30 pf. Using \( \omega = 2\pi \times 10^6 \text{ sec}^{-1} \), \( C = 15 \text{ pf} \) and \( R = 10^4 \text{ ohms} \) gives \( \omega CR \sim 1 \). Thus the error in the measurement of \( C \) can be quite significant, leading to an even larger error in the estimation of \( N_D - N_A \).
Solution

The problem of series resistance may be overcome if in addition to measuring $C'$ the instrument also obtains $G'$ (by detecting the current in phase with $\bar{V}$ on a second phase sensitive detector). Then $C$ may be extracted from $C'$ and $G'$ as

$$C = C' + \frac{G'^2}{\omega^2 C'} \quad (7)$$

A simple substitution of Eqs. (5) and (6) into the R.H.S. of (7) proves this identity. Using suitable calibrations, the outputs $C'$ and $G' / \omega$ can be made available as analog voltages. The squaring, division and addition operations can all be accomplished by appropriate analog circuitry to yield an analog output representing $C$.

The extent of the error made in assuming $RG << 1$ can be determined by substituting Eqs. (2) and (3) into the R.H.S. of Eq. (7). This gives upon simplification the elegant equation (see Appendix)

$$C' + \frac{G'^2}{\omega^2 C'} = C + \frac{G^2}{\omega^2 C} \quad (8)$$

Thus even if RG is not $<< 1$, Eq. (7) will still hold provided $\omega C >> G$. 
Appendix - Derivation of Equation (8)

\[
C' + \frac{G^2}{\omega^2 C'} = \frac{C}{H^2 + \omega^2 R^2 C^2} + \frac{(GH + \omega^2 RC^2)^2}{\omega^2 C/(H^2 + \omega^2 R^2 C^2)}
\]

\[
= \frac{\omega^2 C^2 + G^2 H^2 + 2GH\omega^2 RC^2 + \omega^4 R^2 C^4}{\omega^2 C(H^2 + \omega^2 R^2 C^2)}
\]

Expanding the third term in the numerator gives

numerator = \omega^2 C^2 \left[ 1 + 2GR + G^2 R^2 + \omega^2 R^2 C^2 \right]

\[+ \omega^2 C^2 G^2 R^2 + G^2 H^2 \]

\[= (\omega^2 C^2 + G^2)(H^2 + \omega^2 C^2 R^2) \]

Thus

\[C' + \frac{G^2}{\omega^2 C'} = \frac{\omega^2 C^2 + G^2}{\omega^2 C^2} = C + \frac{G^2}{\omega^2 C^2} \]

References


Figure Captions

Fig. 1. Reverse biased Schottky barrier on epilayer.

Fig. 2. A.C. equivalent circuit of reverse biased Schottky barrier.
Schottky barrier contact

depletion region

epilayer

S-I substrate

Ohmic back contact
List of Symbols

C \quad \text{Capacitance across Schottky depletion region (a.c.)}

C' \quad \text{Equivalent capacitance seen across circuit (a.c.)}

G \quad \text{Leakage conductance across Schottky depletion region (a.c.)}

G' \quad \text{Equivalent conductance seen across circuit (a.c.)}

H \quad RG + 1

j \quad \sqrt{-1}

N_{D-N_A} \quad \text{Net donor density}

R \quad \text{Resistance in series with Schottky barrier}

T \quad \text{Time}

V \quad \text{Applied d.c. bias voltage}

\ddot{V} \quad \text{Small signal a.c. modulation voltage}

V_o \quad \text{Amplitude of } \ddot{V}.

Y \quad \text{A.C. admittance of circuit}

\omega \quad \text{Angular frequency of } \ddot{V}.