A FULL ALTERNATIVE FOR THE RTD QUANTUM-INDUCTANCE EQUIVALENT-CIRCUIT MODEL

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ABSTRACT

Under specific conditions, the small-signal series/parallel double-RC equivalent-network is a novel full mutual alternative for the resonant tunnelling diode quantum-inductance circuit model. Network optimisations to accurately match measured intrinsic impedances of stable, non-oscillating GaAs/AlAs devices, pointed at these conditions. The capacitance C_w of the series-RC branch, peaks needle-sharp at the negative dynamic conductance maximum, indicating carrier discharge from the quantum well. The R_bC_w-time constant equals L_qG_d of the quantum-inductance model, so it is also an indication of the quasibound-state lifetime in the well. For CAD purposes, a very good RTD intrinsic impedance description in the entire bias/frequency space (0-2 V; 0.05-40.05 GHz) is obtained with frequency-independent intrinsic elements, scalable with device area.

INTRODUCTION

Several equivalent circuits for small-signal impedance modelling of double barrier resonant tunnelling diodes (RTDs) are available from literature. We recently studied the application of the RCL or quantum-inductance (QI) model (Fig. 1a; Brown et al [1], Vanbesien et al [2], Kwaspen et al [4,5]). Another model, previously published by researchers from Leeds and Nottingham Universities, U.K. (Miles et al [3]), also can be used to describe measured microwave impedances of GaAs/AlAs based RTDs with symmetric thin barrier and spacer layers. Preliminary optimisations of this series/parallel double-RC network (henceforth indicated as SPdRC; Fig. 1b) to fit the measured data, showed that the R_bC_w-time constant of the series-branch behaved almost similar as the L_q/R_d-time constant of the QI-model. A mathematical impedance analysis of both models shows that, under specific conditions, the SPdRC equivalent network is a full alternative for the QI-model. While the last has four frequency-independent intrinsic elements to describe the measured impedance 'perfectly', the SPdRC-network has one degree of freedom more. The specific conditions reduce the redundance and a novel full mutual alternative is obtained. Repeated optimisations with these conditions set, resulted in a very good description of the measured intrinsic RTD-impedances throughout the whole 0-2 V bias-voltage and 0.05-40.05 GHz frequency ranges.

MODEL DESCRIPTIONS AND EQUIVALENCE-CONDITIONS

The small-signal dynamic device resistance R_d (R_D) (Fig. 1), should agree the differential resistance derived from the DC I-V curve of the stable RTD. C_d (C_D) is the dynamic device capacitance. The authors of the SPdRC-model [3], denoted C_w to represent the charge in the well while R_b is the resistance of the barrier closest to the cathode. R_S describes contact and spreading resistances and L_q is the intrinsic quantum inductance. The impedances Z_{QI} and Z_{SPdRC} of both intrinsic RTD models are in a certain stage of the analysis:

$$Z_{QI} = (R_d + j\omega L_q)/((1-\omega^2 C_d L_q) + j\omega R_d C_d) + R_s \quad (1)$$

$$Z_{SPdRC} = (R_D + j\omega R_b R_D C_w)/((1-\omega^2 R_b R_D C_D C_w) + j\omega(R_D C_D + R_b C_w + R_D C_w) + R_s \quad (2)$$

Intended to describe the same intrinsic RTD, comparison of the model impedances, term by term, leads to :

$R_d = R_D$, $L_q = R_b R_D C_w$ and $C_d L_q = R_b R_D C_D C_w$ which gives $C_d = C_D$, and

$$R_d C_d = R_D C_D + R_D C_w + R_b C_w \quad (3)$$

When the condition $R_b = -R_D$ ($= -R_d$) is set in the SPdRC-model, $R_D C_w + R_b C_w$ of equation 3 cancel out, and a full mutual alternative is obtained ($Z_{QI} = Z_{SPdRC} = Z_d$). One model can be expressed into the other one. Then the time constant $L_q/R_d = L_q G_d$ can be written as $R_b C_w$.

MEASUREMENTS AND OPTIMISATION RESULTS

The RTD under test, is a 6 µm square device with a 5 nm GaAs quantum well and symmetric 2.5 nm thick AlAs barriers and GaAs spacer layers, all undoped, plus upper and lower contact layers on a semi-insulating substrate (Fig.2).

A microwave reflection coefficient array $S_{11}[V_b,f]$, on-wafer measured on this RTD under stable, non-oscillating conditions, was used as input for an optimisation process that matches the SPdRC circuit response to the measured data. The S_{11} datasets (bias range 0-2 V, 75 points; frequency range 0.05-40.05 GHz, 401 points) of the extrinsic RTD were converted to a measured impedance array $Z_d[V_b,f]$ of the intrinsic RTD, by using measured data of reference structures that describe the behaviour of the interconnections on the substrate, from the S_{11}

measurement plane to the RTD-mesa (Fig. 3; [4]). The measured and modelled real and imaginary parts of Z_d are compared and the model is optimised (for each bias point) for minimum absolute errors. The $R_b = -R_D$ condition is set during the optimisations. Fig. 4 shows an example of a match at 1.0090 V bias in the active region. In this way, all 75 bias points are treated and the optimised model elements are assembled to give Fig. 5b-c. R_s has an average value of 9.5 Ω. Fig 5a shows the measured DC I-V curve of the stable, non-oscillating RTD at 21^{o}C [4]. Fig 5d gives the measured and modelled resistive cut-off frequency f_r against bias voltage (See also Fig. 4a). From the optimised independent elements, the time constants $R_b C_w = L_q G_d$ (peak ~22ps at 1.0008-1.0124 V) and $R_d C_d$ are calculated (Fig. 6a,b). Note that the extreme values of $R_b C_w$ at the peak and valley voltages are less reliable, since G_d (G_b) goes through zero there.

DISCUSSION

In contrast to the conclusion about the C_w-peak location in [3], the network optimisations on our RTD, set the onset of C_w at the current maximum, while C_w and G_d peak at the same bias, so C_w indicates only charge transfer out of the quantum well. The distorted I-V curve in [3], due to relaxation oscillations, probably led to the faulty statement. C_d behaves generally as a depletion capacitance. Because G_b and G_d are reversed by the equivalence condition set, G_b and C_w are negative in the passive regions to give a positive L_q. However, the influence of the series-branch in these regions is very limited, since, from optimisations, C_w is very small, because the Esaki-subcircuit (R_d, C_d and R_s) is sufficient for a good fit of measured and modelled Z_d in the passive regions. The time constant $L_q G_d = R_b C_w$ should be an indication of the quasibound-state lifetime in the well [1,2]. The calculated ground-state lifetime for a barrier thickness of 2.55 nm is ~ 50 ps and changes exponentially to ~ 18 ps for 2.26 nm thickness (1 monolayer decrease). This compares well with a time constant of 22 ps measured at 1.0072 V (Fig. 6a). The f_r-curves match very well, an indication of a good model fit, so this paper reflects also a plea for impedance measurements on stable, non-oscillating RTDs when extracting model parameters.

For CAD purposes, a very good RTD intrinsic impedance description in the entire bias/frequency space (0-2 V; 0.05-40.05 GHz) is obtained with frequency-independent intrinsic elements, scalable with device area.

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** Mr van der Vleuten passed away in May of this year.

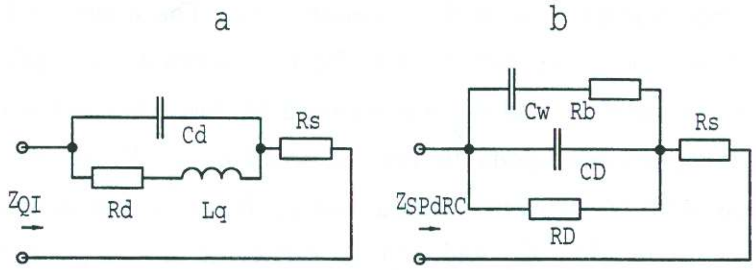

Fig. 1 Intrinsic RTD equivalent-circuits
a Quantum-inductance model
b Series/parallel double-RC network

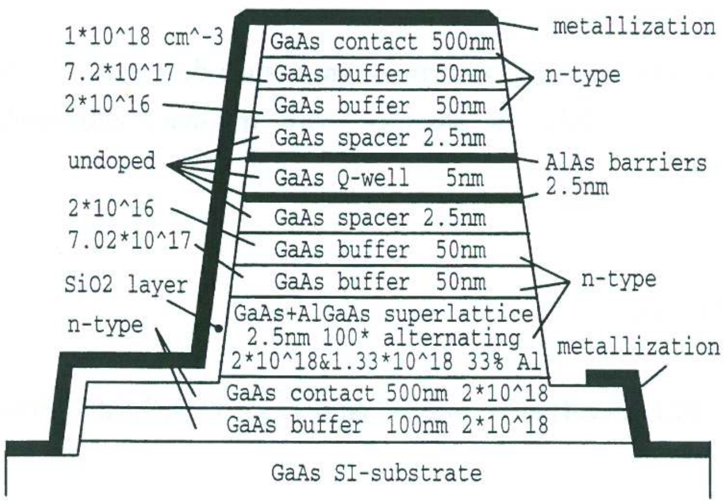

Fig. 2 RTD layer structure

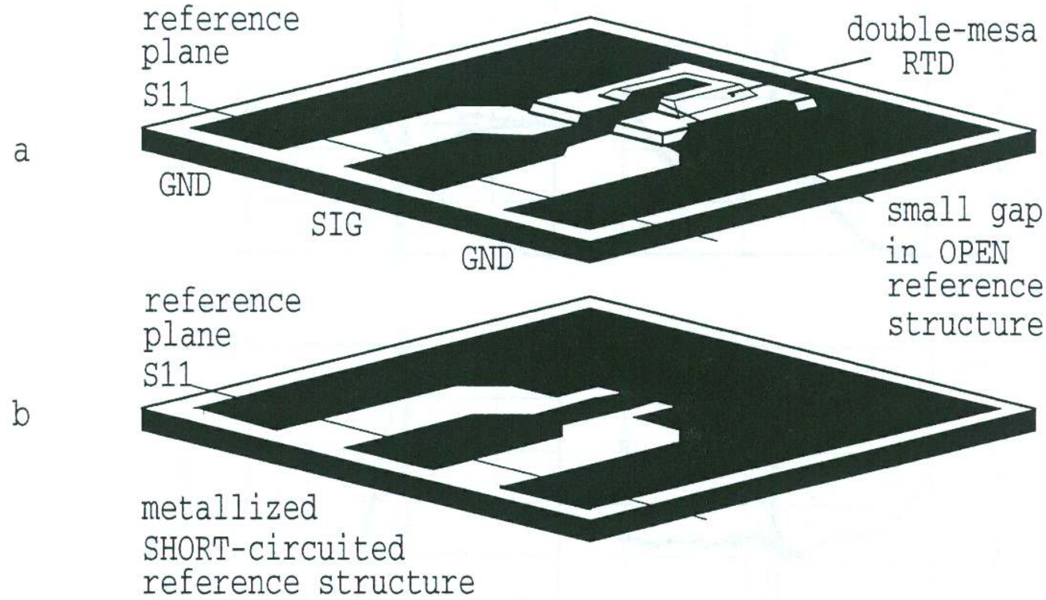

Fig. 3 Planar RTD with coplanar microwave probe access and metallized reference structures SHORT and OPEN
a planar RTD with double-mesa structure
b short-circuited reference structure to determine the elements of the extrinsic model

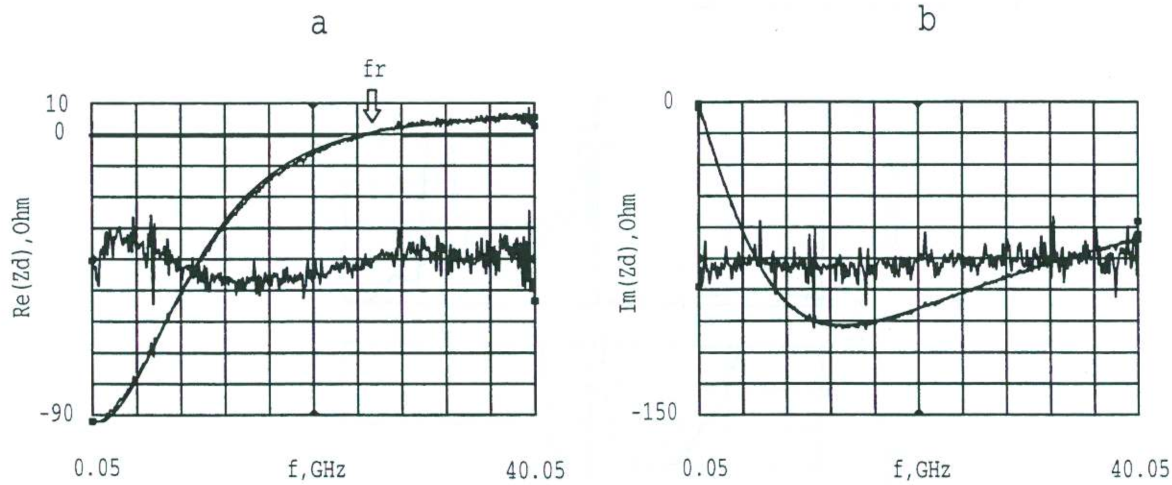

Fig. 4 Measured and modelled intrinsic impedance Zd of RTD @ 1.009 V ; Noisy curve is difference measured-modelled (2 Ohm/div; center= 0)
a real part of Zd against frequency f (GHz)
b imaginary part of Zd against frequency

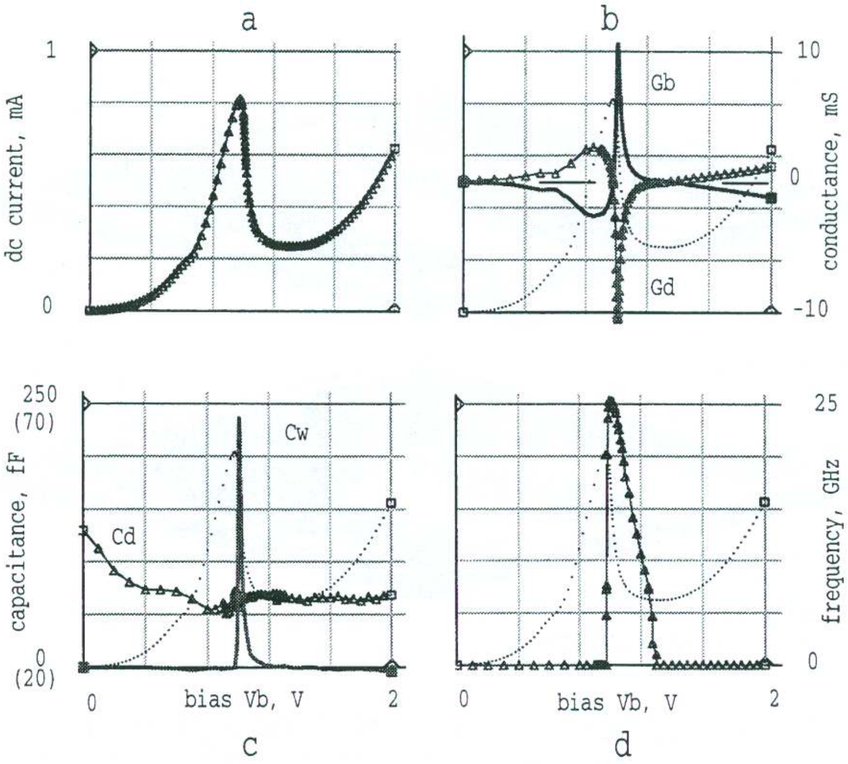

Fig. 5 Results measurements and optimisations
a measured DC I-V curve; also dotted lines in Fig. 5b-d
b dynamic conductances Gb, Gd [mS] against bias-voltage Vb
c dynamic capacitances Cd and Cw against Vb.
ranges are 20-70 fF (Cd) and 0-250 fF (Cw)
d measured (-) and modelled (Δ) resistive cutoff frequency fr in GHz

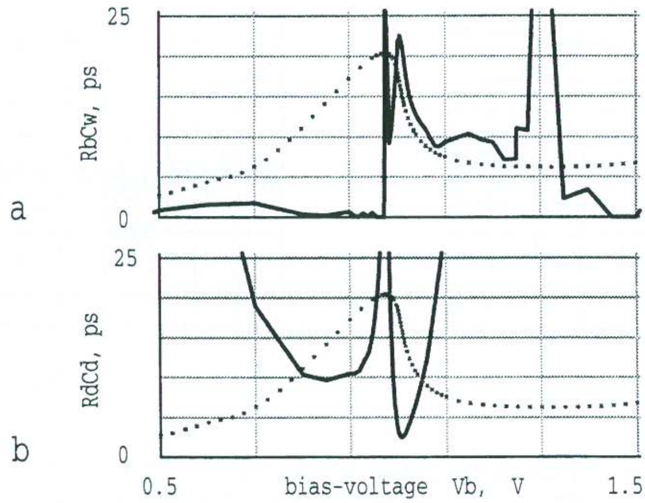

Fig. 6 Time-constants RbCw and RdCd
Dotted line is DC current (1 mA f.s.)
a RbCw (= LqGd; in ps) against bias Vb
b |Rd|.Cd (= |Rb|.Cd; in ps)