Characteristics of a Coplanar Waveguide HEMT Mount on GaAs Substrate

D. Mirshekar-Syahkal and Adrian Pote

***Abstract*—In a special integrated coplanar waveguide HEMT mount, designed for a wide band (1–60 GHz) on-wafer measurement of the characteristics of HEMTs on GaAs, significant power loss as high as 30% of the input power over a range of frequencies is observed. This power loss is mainly attributed to the radiation through two via holes connecting the coplanar waveguide ground planes to the backside metallization in the mount. Based on this assumption, an approximate theoretical model is developed to substantiate the experimental observations.**

I. Introduction

Monolithic circuit technology based on GaAs and InP is rapidly developing for microwave, millimetre-wave and electro-optic applications. In this technology, active devices like FETs and HEMTs are the key circuit elements. New generations of these devices are currently under research and development. The work presented in this paper stems from such an activity where a wide-band (1–60 GHz) characterization of some HEMTs on GaAs is required. The device is developed within a coplanar waveguide (CPW) mount on a high resistivity GaAs substrate. Fig. 1 shows the schematic diagram of the mount with and without a HEMT. The ground planes of the CPW have finite widths (160 μm) which are comparable to the substrate thickness (h = 130 μm), but these parameters are much smaller than λ_d = 1.39 mm, the wavelength in GaAs (ε_r = 12.9) at the highest frequency of interest. The via holes in the mount are basically to ground the backside metallization. In certain applications where a transition from the mount to a microstrip line is required such grounding is essential. In order to evaluate the performance of a device, the characterization of the mount is vital. This paper examines the characteristics of the mount shown in Fig. 1 and introduces an approximate theoretical model to support the experimental observations.

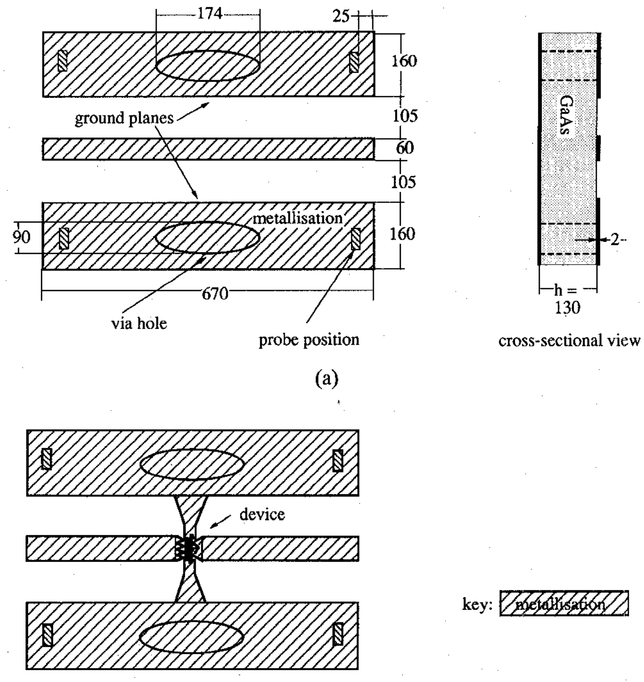

Fig. 1. Plan view of coplanar waveguide HEMT mount; (a) without a device, (b) with a device. Dimensions are approximate and in μm. Conductors are gold (σ = 4.1 × 10^7 S/m) and the substrate is GaAs (ε_r = 12.9 and tan δ = 0.001).

II. Characteristics of the Mount

Two typical measurements of the S-parameters associated with two CPW mounts, taken at different times while each time the measurement system was recalibrated, are shown (by solid lines) in Fig. 2. The approximate dimensions of the mounts together with other information are shown in Fig. 1.

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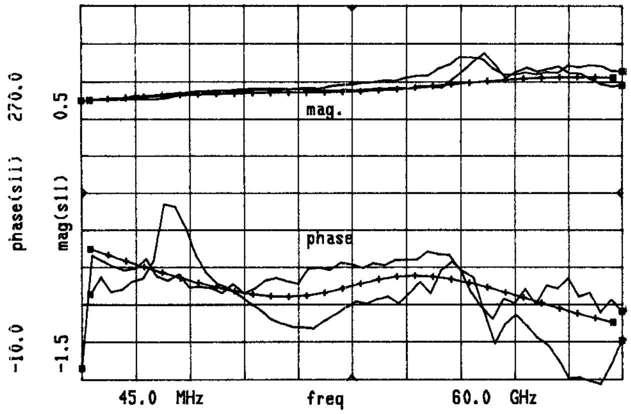
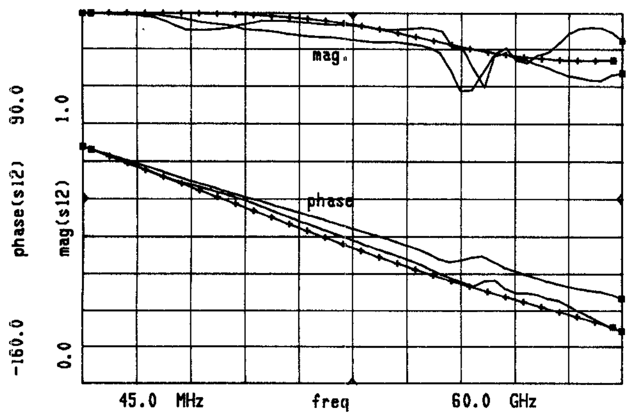
Also the S-parameters of two CPW mounts measured prior to thinning their substrates (h = 500 μm) and etching their via holes are shown (by solid lines) in Fig. 3. At this stage of the fabrication of the mount, the backside metallization is not present, but will exist in practice when the wafer is positioned on the test station. Thus, the structure is expected to have a behavior similar to that of a mount with backside metallization, but without via holes.

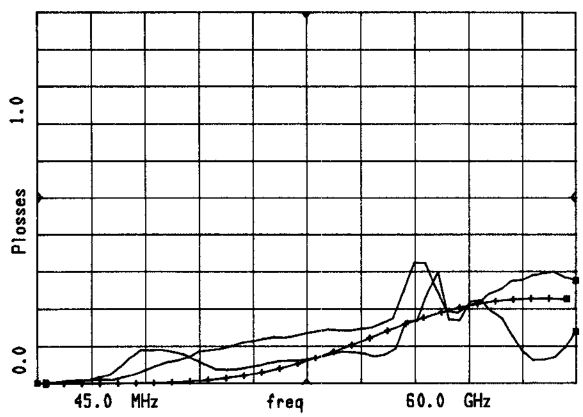
The S-parameter measurements presented in Fig. 2 and Fig. 3 were taken using the HP-8510C network analyzer in conjunction with the Cascade Microtech coplanar waveguide on-wafer probe. The network analyzer was calibrated with the LRM technique while employing the Cascade Microtech LRM impedance standard substrate [1]. The measurement uncertainty stemming from probe placement, calibration and residual errors in the measurement system, is believed to be less than 0.4 dB for magnitudes and less than 6° for phases over 1–60 GHz range [2].



(a)

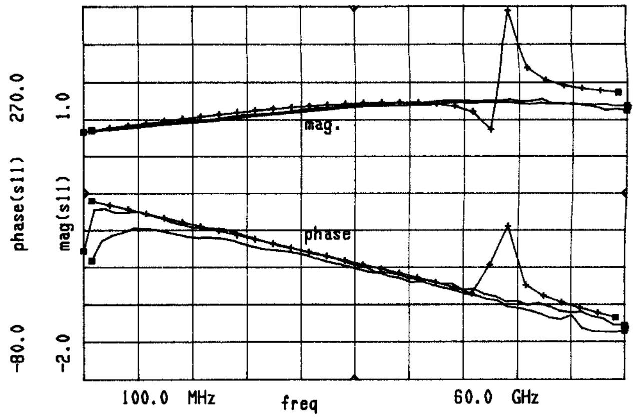


(b)

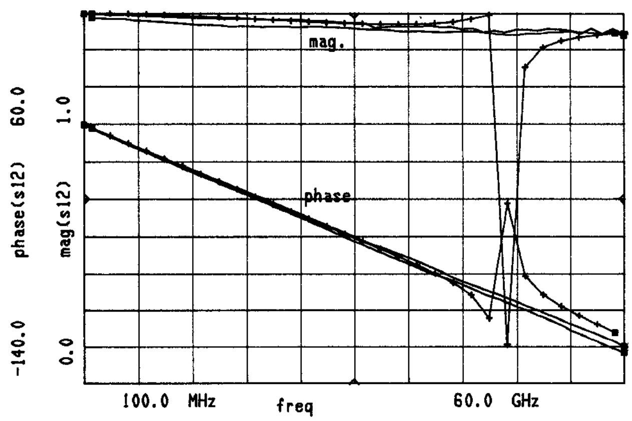


(c)

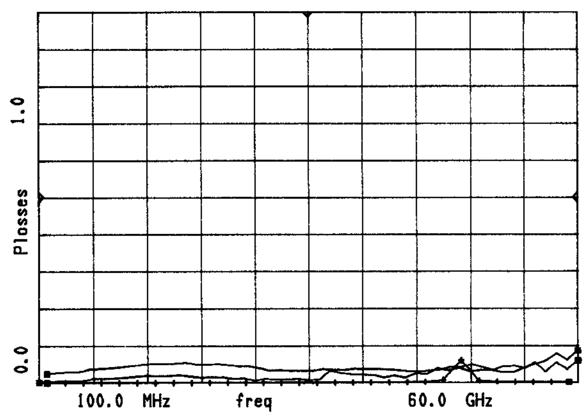
Fig. 2. (a)–(b) Measured scattering parameters and (c) the power loss for two mounts along with the results of modelling; measurement (——), modelling (+—+—+).



(a)



(b)



(c)

Fig. 3. (a)–(b) Measured scattering parameters and (c) the power loss of two incomplete (unthinned via-less) mounts along with the theoretical (simulated) results; measurement (——), simulation (+—+—+).

In Figs. 2–3, the quantity

$$P_{\text{losses}} = \text{Lost power/Input power} = 1 - \left(|S_{11}|^2 + |S_{12}|^2\right)$$

representing the normalized loss of power from the mounts is also plotted, (Fig. 2(c) and Fig. 3(c)). If a mount is lossless, $P_{\text{losses}} = 0$ and hence the above expression reduces to the well-known expression $|S_{11}|^2 + |S_{12}|^2 = 1$.

As seen in Figs. 2–3, although the two sets of measurements do not coincide at all points due to uncertainties in the fabrication of the mounts and in the measurements, they do show the same quantitative behavior. Of special concern is the excessive loss of power in the mounts, as shown in Fig. 2(c), which consistently occurred in all samples fabricated.

Since the CPW involved in the mount has finite width ground planes, it cannot support a parallel plate TEM wave, which is a source of a significant power loss [3]–[4]. Such a power loss occurs because the phase velocity of the TEM wave is less than that of the CPW wave [5]. Considering [5]–[6], the observed excessive power loss cannot be attributed to the power leakage (radiation) from the CPW mode to the TM_0 surface mode of the substrate through the CPW line *itself*, because the cross-over frequency of the two modes is well beyond the frequency range of interest and hence the amount of radiation should be negligible (and therefore is not considered in the modeling introduced later). Also, the phenomenon cannot be solely attributed to the conductor and substrate losses of the CPW mount, because these losses are usually small and monotonically increase with frequency [7]. Fig. 3(c) is the evidence to the mentioned facts. This figure shows that the total loss including radiation, conductor and dielectric losses for the two via-less CPWs on unthinned substrates is very small and except for some small variations (which can be attributed to measurement uncertainties for small losses), the total loss increases with frequency.

It is possible that a CPW with finite ground planes and backside metallization supports three modes (slot mode, microstrip mode and coplanar waveguide mode) with no cutoff frequency [8]. Initially a mode conversion from the CPW mode to the two other modes was suspected as being the cause of the power loss. Specifically, it was suspected that a mode conversion from the CPW mode to the microstrip mode could take place and the converted power would be reflected to the source by via holes short circuiting the mode. But in view of [8] a power conversion to the microstrip and to the slot modes cannot be significant, since the input/output probes are not of microstrip type and the coplanar waveguide probes are positioned on the mount symmetrically. This is evident in Fig. 3 where no unexpected variation in the phases of the scattering parameters over the concerned frequency range as a result of a multimode propagation is noticed. Furthermore, except around a resonance in the theoretical results which is an artifact due to an enclosure introduced around the structure to simplify the computation task, the experimental results in Fig. 3 are in good agreement with the results of simulations when considering only the propagation of the CPW wave on the unthinned structure.

The simulations presented in Fig. 3 were carried out using EM software [9]. The software is based on the spectral domain technique [10] and can take into account the conductor and dielectric losses. These losses have been duly accounted for in all simulations presented in the paper.

In view of the given evidence, the only remaining source of the excessive power loss is radiation, occurring into space and substrate as a result of the vias between the CPW ground planes and the backside metallization. The CPW wave incident on the vias produces a current along the vias and since there is no metallic return path for this current, it gives rise to a strong coupling between the CPW mode and the continuous (radiation) and discrete (surface wave) modes. In other words, the vias act as radiating elements. Based on this assumption, a very approximate model of the mount is introduced to verify the validity of the assumption.

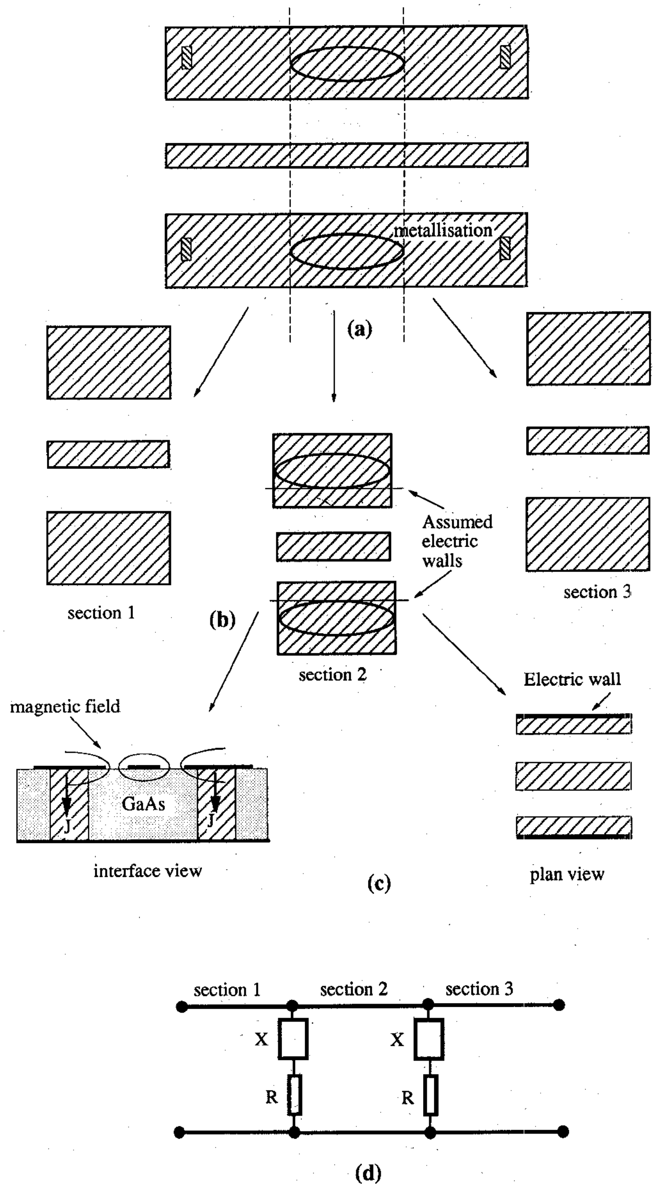


Fig. 4. (b)–(c) Partitioning of the coplanar waveguide mount (a) into three sections, (d) an equivalent circuit for the mount.

III. Modeling

An accurate analysis of the HEMT mount including the coupling of the energy from the CPW mode to the surface and space wave modes through the vias, is complex and outside the scope of this work. Such analysis of the problem would involve the solution of the scattering of the CPW wave by two posts acting as the via holes. An alternative approach adopted here uses approximations based on physical insight into the problem.

The HEMT mount, Fig. 4(a), is divided into three sections as shown in Fig. 4(b). The first and the third sections are coplanar waveguides with finite ground planes and backside metallization. The scattering parameters of these sections were obtained using EM software [9].

The second section consisting of the vias cannot be accurately modeled by EM software, since the software cannot handle the metal boundary at the vias nor can it handle the coupling of the CPW wave to radiation at the vias. To circumvent this problem, the second section has been imagined as two elements. One element represents a shunt impedance corresponding to the reactance of the vias and a radiation resistance, and the second element is a transmission line connecting the other two sections.

The reactance of the vias is basically inductive, specially at low frequencies, corresponding to a current flow produced by the incident CPW wave in the vias, Fig. 4(c), and becomes a combination of capacitance and inductance at higher frequencies. The approximate value of the reactance was obtained by computing the scattering parameters of the vias using EM software. This inductance should be higher than that experienced in practice, because EM software assumes current flow along the vias from any point around the periphery of the vias whereas the actual inductance in the present case is mainly due to the current flow along those parts of the vias constituting discontinuities between the first and second sections and between second and the third sections.

The second element of the second section, the transmission line, can be assumed as a coplanar waveguide with electric side walls located tangent to the boundaries of the two vias as shown in Fig. 4(b) and Fig. 4(c). Such an assumption was also used very recently in [11]. This model for the line can be justified on the grounds that the vias have metal boundaries and as a result the CPW field should be negligible beyond the space between the two vias. The assumed transmission line, which was analyzed by EM software, has an impedance different to those of the CPWs of the first and the third sections.

Of course, the approximate model introduced above for the second section is not accurate, but considers the effect of the impedance arising from the scattering of the CPW wave by the vias and takes into account the effect of the change of the impedance of the second section of the mount due to the metal boundary of the vias.

Combining the three sections, an equivalent circuit for the mount as shown in Fig. 4(d) can be formed. The resistors (R) in the circuit represent the power loss in the forms of the surface and the space waves. In the equivalent circuit, the reactance of the vias found by EM software is distributed equally between the two ends of the line located in the middle of the model, Fig. 4(d).

Considering the dimensions of the substrate and the frequency range, it is easy to deduce that the substrate supports a TM_0 surface wave only in its weak form (i.e., the surface wave field is not strongly bound to the substrate) [12]. Therefore the radiation resistance (R) in the equivalent circuit can be expressed as $R = a10^{-21}f^2$ where "a" is an unknown parameter. This expression is based on the well-known radiation resistance of a Hertzian monopole. Again the choice of the expression is very approximate and should be considered as a zero-order approximation to true R.

The scattering parameters of the first and third sections as well as those of the elements in the second section were employed to calculate the scattering parameters of the equivalent circuit of the mount, Fig. 4, over the frequency range of interest. Since parameter "a" was unknown, the calculations were carried out over a range of "a" ascending from a very small value. For a rapid calculation, MDS software [13] was used in this part of the work. For the given range, the responses of the model are obtained and compared to the measured results. For "a" around 100, the simulated power loss shows the closest behavior to that experimentally observed, Fig. 2(c), although it is lower than that measured at low frequencies. However, such discrepancy due to measurement uncertainties for small losses is expected. For this value of "a," the scattering parameters also behave similarly in the experimental and simulated results, Fig. 2(a) and Fig. 2(b), specially the phase match seems excellent. It should be noted that a behavior similar to a resonance observed around 42 GHz in the experimental data may be due to the resonance of the piece of line between the vias and the connection of the CPW probe to the coaxial line or it could be due to a transverse resonance between the two vias, although the latter is the less likely cause when comparing the wavelength with the distance between the two vias.

IV. Conclusion

Experimental characteristics of a coplanar waveguide HEMT mount including two via holes connecting the backside metallization to the CPW ground planes were presented. An approximate model was developed to explain the existence of an excessive power loss in this mount. The loss is believed to be mainly due to radiation in the forms of surface and space waves from vias. This was supported by comparing the results of simulations and measurements. The circuit elements in the model were computed using available commercial software. Further theoretical work is required if an accurate characterization of the mount is necessary, since commercial software presently available does not offer the capabilities required for analyzing problems of similar nature.

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Adrian Pote, photograph and biography not available at the time of publication.