Fabrication, Testing, and Lumped Element Modeling of Planar Heterostructure Barrier Varactors

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Abstract—In this paper we present a novel lumped element model of planar InGaAs/InAlAs/AlAs Heterostructure Barrier Varactors (HBVs) on InP substrate. HBVs with 30 and 40 μm anode diameters were fabricated as coaxial-type configuration to check the wafer quality and extract the intrinsic parameters. Planar HBVs mounted on a coplanar waveguide were fabricated and measured in the 0.5–26.5 GHz frequency range, at different bias points up to 10 V. The measured S-parameters were fitted to the proposed equivalent circuit to extract the values of both the parasitic and intrinsic elements. Finally, the extracted equivalent circuit was used to calculate the theoretical tripling efficiency at 450 GHz attainable with the fabricated HBVs.

I. Introduction

Frequency multipliers based on Heterostructure Barrier Varactors (HBVs) received considerable attention in the last decade for power generation above 200 GHz. In fact, the even symmetry of the C-V characteristic and the odd symmetry of the I-V characteristic of HBVs lead to the generation of only odd harmonics [1]–[3], thus avoiding DC bias circuitry and idler circuits at the even harmonics. The problem with the excessive leakage current is solved with the introduction of an AlAs barrier in the InGaAs/InAlAs material system on InP substrate [4]. High performance HBVs based on InGaAs/InAlAs/AlAs material system working in the range 200-300 GHz have been recently reported [5]–[7].

In this paper, the performance of planar HBVs for frequency tripling at 450 GHz is investigated. Both coaxial and planar HBVs were fabricated using the process described in Section II and measured in the 0.5–26.5 GHz frequency range. The parameters of a simple lumped element circuit representing the intrinsic device were extracted from the measurements of the coaxial–type HBVs. This lumped element circuit was used as a starting point for fitting the measured S-parameters to the proposed novel equivalent circuit, which account for both the parasitic and intrinsic elements.

Finally, the extracted equivalent circuit was used to calculate the theoretical tripling efficiency at 450 GHz attainable with the fabricated HBVs.

II. Technological Issues

The InGaAs/InAlAs/AlAs heterostructure barrier varactor is grown with Molecular Beam Epitaxy on SI InP substrate. The barrier is formed with two AlAs layers in order to reduce the leakage current which occurs mostly due to Γ-X transition [8]. The MBE-grown epitaxial structure of the HBV is shown in Fig. 1. The HBVs were fabricated using standard photolithography techniques. Firstly the coaxial HBVs (Fig. 2) were fabricated in order to check the quality and extract the intrinsic parameters. Ohmic contacts are formed by alloying the Ti/Pt/Au metallization structures for 1 minute at

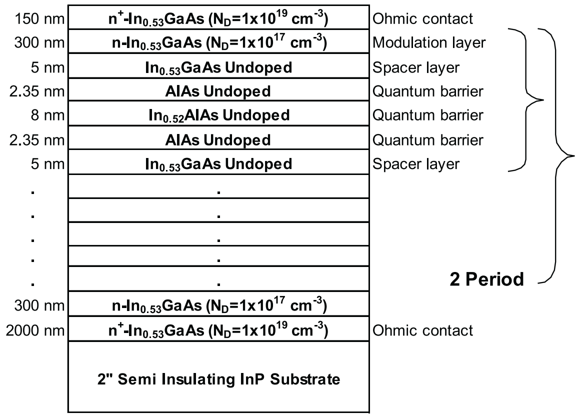

Fig. 1. Wafer design of a MBE grown two-barrier HBV.

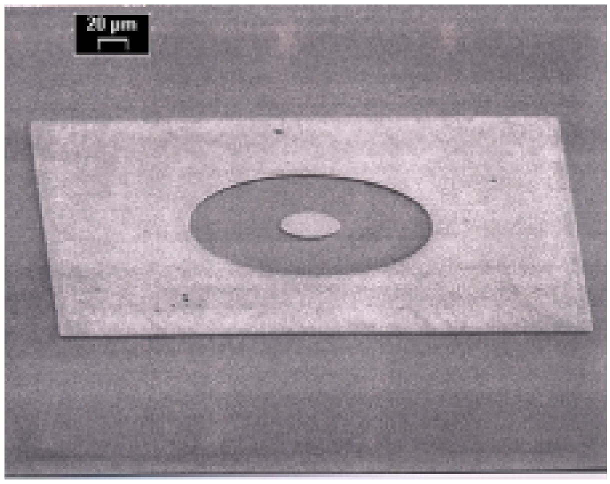

Fig. 2. SEM picture of coaxial HBV.

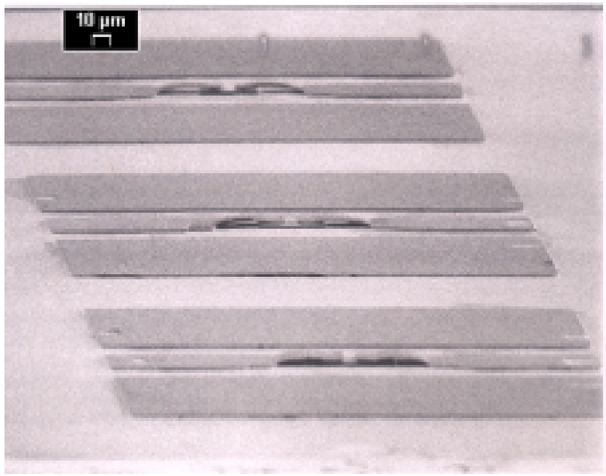

Fig. 3. SEM picture of the two-column four-barrier HBVs embedded in a coplanar environment.

200° C in H_2-atmosphere. The mesa is formed using wet-etching technique ($A_{eff} = 38\ \mu$m). The small-signal equivalent circuit is extracted from the measured S-parameters between 0.5–26.5 GHz which will be later used for an initial estimate for the planar approach.

Following the coaxial test of the wafer the planar HBVs were fabricated. Ohmic contacts are formed by alloying the Ni/Ge/Au/Ti/Au metallization structures for 40 seconds at 400° C in H_2-atmosphere [9]. Despite the different ohmic-contact fabrication processes a small effect on series resistance is expected —with a specific resistance of $10^{-6}\,\Omega cm^2$ the contact contributes with less than $1\,\Omega$ to the total series resistance. The mesa and pad isolation is formed using wet-etching technique followed by air-bridge formation. The mesas are etched with a slow etch rate (180 nm/min) in order to control under etching. Two-column four-barrier HBVs with effective diameters of 8, 13, 18 μm were fabricated as coplanar configuration is order to test with wafer probe station as shown in Fig. 3.

III. Lumped Element Modeling and conversion efficiency calculation

As a first step for obtaining a lumped element model for the coplanar HBV structure (see Fig. 3) we extracted the intrinsic parameters from the measurement of the coaxial structure (Fig. 2) in the frequency band 0.5–26.5 GHz.

We considered the simplified lumped element circuit shown in Fig. 4 and implemented a computer code for calculating the parameters R_s, $C(V)$ and $I(V)$. The code is based on the minimization of an *error function*, which is defined as a summation of the differences between the measured one–port scattering parameters (for a given bias V) and the ones calculated for given values of R_s, C and I. Using this code, we extracted a value $R_s = 6.5\,\Omega$ and the C-V and I-V curves shown in Fig. 5 in the case of an HBV effective diameter of $28\,\mu$m.

The parameters extracted in the previous step have been used as a starting point for obtaining an accurate lumped element model of the coplanar HBV structure of Fig. 3. In particular, we considered the circuit shown in Fig. 6, which takes into account the parasitic effects introduced by the planar structure as well as the intrinsic non-linear elements of the HBV. Especially the simple representation of the air bridge through lumped reactive elements seems to be accurate enough. Using the same

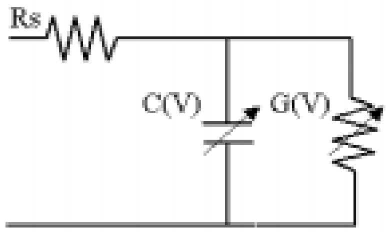

Fig. 4. Simple lumped element circuit considered for extracting the intrinsic parameters of the HBVs from the measurements of the coaxial structure.

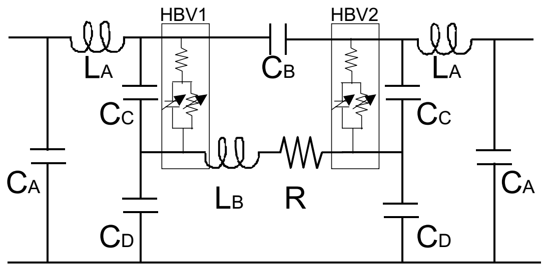

Fig. 6. Lumped element circuit considered in the case of the coplanar HBV structure; the boxed regions represent the equivalent circuit of the HBV structures.

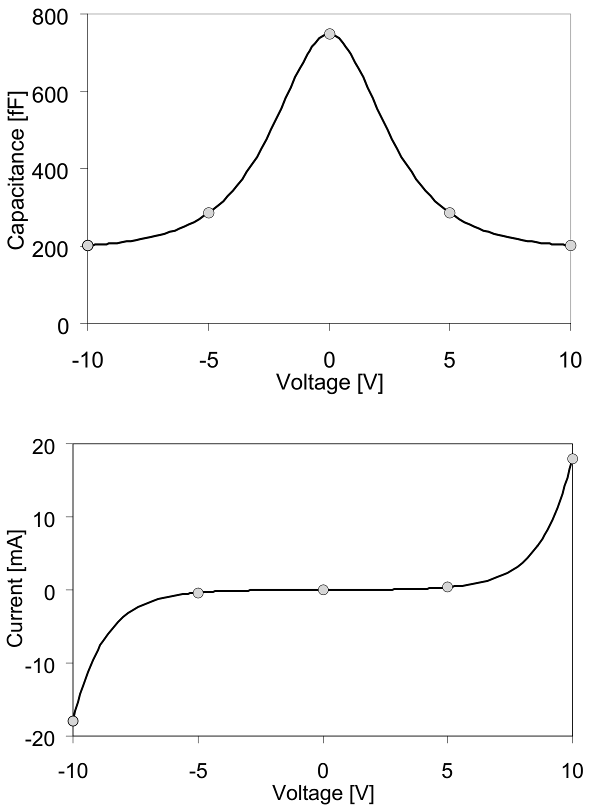

Fig. 5. C-V and I-V curves extracted from the 0.5–26.5 GHz measurements of the coaxial HBV structure.

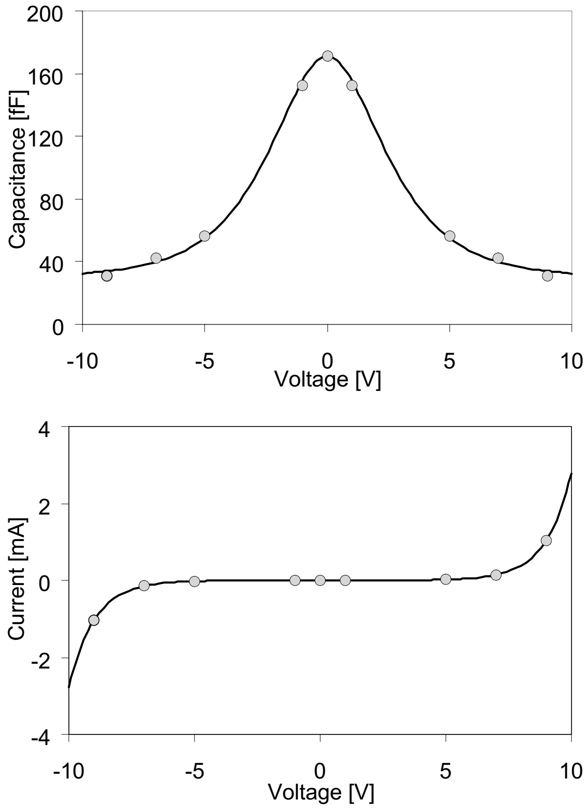

Fig. 7. C-V and I-V curves extracted from the 0.5–26.5 GHz measurements of the coplanar HBV structure.

technique considered in the previous case, we implemented a code for the extraction of the values of the lumped elements from the two-port measurement. The results in the case of a coplanar structure with diameter of $18\,\mu$m are $R_s = 3.0\,\Omega$, $R = 10^{-8}\,\Omega$, $C_A = 10.2\,fF$, $C_B = 16.7\,fF$, $C_C = 63.3\,fF$, $C_D = 20.4\,fF$, $L_A = 43.4\,pH$, $L_B = 3.6\,pH$. Moreover, the C-V and I-V curves are shown in Fig. 7.

Once the lumped element model of the HBV has been determined, the conversion performance of the multiplier is calculated by a novel method based on the combination of the standard Harmonic Balance (HB) technique and the Genetic Algorithm (GA) [10].

IV. Conclusion

This paper presents a new approach to the modelling of planar HBV's for the design of submillimetre wave frequency multipliers. The nonlinear elements as well as the parasitic effects introduced by the planar structure are properly accounted for in the form of an equivalent circuit. Furthermore, the accuracy of the large-signal model of the intrinsic, non-linear HBV elements is automatically validated by the absence of parasitic effects in the coaxial structure they are obtained from. Finally, the equivalent circuit has been used to perform conversion performance calculations.

The philosophy of this approach can be extended to practically all planar non-linear devices operating at sub-millimeter frequencies, for which parasitics become of considerable importance. The clear separation of linear and non-linear effects ensures the quality of the model.

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