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Characteristics of Submicron HBTs in the 140-220 GHz Band

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We report the measurement of submicron transferred-substrate InGaAs/InAlAs heterojunction bipolar transistors (HBTs) in the 140-220 GHz frequency band. We believe this is the first reported characterization of HBTs above 110 GHz. Previous measurements of transferred-substrate HBTs have predicted record values of power gain cutoff frequency f_{max} by extrapolating at –20 dB/decade the unilateral power gain measured at 110 GHz [1]. Due to uncertainties associated with our measurement techniques, the unilateral power gain could not be determined for higher-gain devices. Additionally, transistor S-parameters measured in the 140-220 GHz band do not correlate well with a hybrid-pi model derived from measurements at lower (6-45 GHz) frequencies.

The MBE layer structure and fabrication process are similar to those described in [2]. Electron-beam lithography was used to define submicron emitter and collector stripes. Two layer structures were considered. One layer structure consisted of a 40 nm base and a 300 nm collector. This layer structure was representative of that used for previously reported high f_{max} transistors [1]. The second layer structure had a 30 nm base, and a 150 nm collector. Devices on this layer structure were expected to have higher current gain cutoff frequencies f_τ, and a lower f_{max}: f_τ ratio.

On-wafer measurements used an HP8510C network analyzer with Oleson Microwave Labs frequency extenders, connected to GGB Industries wafer probes via short WR-5 waveguides. Calibration used on-wafer Line-Reflect-Line (LRL) standards with extended reference planes for reduced probe coupling. The standards were measured after calibration to partially verify the calibration accuracy. The measurement of the through line standard showed the magnitude of S_{11} and S_{22} to be < –30 dB, and S_{21} had < 0.2 dB variation in amplitude and < 3° variation in phase. Measurement of the open standard showed an amplitude variation of < 0.1 dB and a phase variation < 3°. Fig. 1 shows the measurements of the reflection coefficients for the through and open standards after calibration. Also shown on the graph is S_{21} for a long 50 Ω line that was not used in the calibration. The measurement shows smooth amplitude and phase variation, as expected of a well-calibrated measurement.

Fig. 2 shows the unilateral power gain (U), the maximum stable gain (MSG), and the short circuit current gain ($h_{21} \sim f_\tau/jf$) for a device measured from 6-45 GHz and 140-220 GHz. The device was fabricated on 300 nm collector material, and had emitter and collector stripe widths of 0.4 µm and 0.7 µm, respectively. The unilateral gain is not plotted in the 140-220 GHz band because measurements showed large variations in the parameter. At spurious intervals in the band the calculated U increases to infinity and then becomes negative. This effect is due to the very high transistor output impedance. At high frequencies the HBTs have low series input resistance ($\sim R_{bb}$) and extremely low shunt output conductance $G_{22} \approx j2\pi f C_{cbi} h_{21}$, with the latter parameter being largely responsible for the high HBT power gain. Because of this very low G_{22}, $\|S_{22}\|$ is very close to unity, and small variations in the measured S_{22} result in large variations in the measured G_{22} and U. Extrapolating U from the 6-45 GHz measurements at –20 dB/decade predicts an f_{max} of ~ 600 GHz.

The measured S_{12} shows a rapid increase in magnitude over the 140-220 GHz range, increasing much more rapidly than expected given a fixed and frequency-independent collector-base capacitance C_{cb}. Consequently, the measured $\text{MSG} = \|S_{21}/S_{12}\| \sim 1/\omega C_{cb}[R_{ex} + kT/qI]$ decreases more rapidly than the theoretical -10 dB/decade. The anomalous S_{12} may be due to spurious probe-probe coupling or coupling between transistor input and output transmission-lines through substrate electromagnetic modes.

A hybrid-pi model was derived from the 6-45 GHz measurements. The model is shown in Fig. 4, and the simulated S-parameters are included in Fig. 3. The modeled S_{11} and S_{22} are in poor agreement with measurements in the 140-220 GHz band. However, measurements of a single-stage amplifier using these devices were found to be in close agreement with simulations using the measured transistor S-parameters [3]. Measured amplifiers exhibit > 6 dB gain per transistor at 180 GHz, which is consistent with high transistor available power gain [4].

Fig.5 and Fig. 6 show the measured gains and S-parameters for a transistor with a 150 nm collector. The device had emitter and collector stripe widths of 0.7 µm and 1.0 µm. The thinner collector results in a higher C_{cb}, and thus a larger output conductance. The measurement of U appears well-behaved, decreasing at ~ -20 dB/decade. The f_{max} and f_τ of the device are estimated to be ~ 220 GHz and ~ 200 GHz, respectively. 140-220 GHz measured parameters of this HBT are again not consistent with that of a hybrid-pi model developed from 6-45 GHz measurements.

We believe this work represents the first attempt to accurately characterize transistors of any type in the 140-220 GHz band. The measured devices show evidence of high transistor power gain at submillimeter-wave frequencies. However, at this time, the measurement uncertainty is too large to accurately quantify the device performance in this band. This work was supported by the ONR under grant no. N0014-99-1-0041.

[1] Q. Lee *et al.*, *1999 IEEE Device Research Conference, Santa Barbara, CA.(postdeadline)*
[2] Q. Lee *et al.*, *1999 IPRM, Davos, Switzerland.*
[3] M. Urteaga *et al.. To be presented 2001 MTT-S, Phoenix, AZ.*
[4] M. Urteaga *et al.. To be submitted.*

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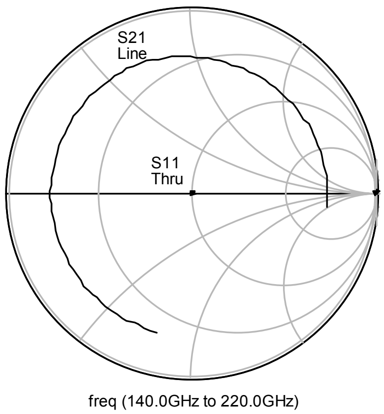

Fig. 1. Measurements of calibration standards after LRL calibration.

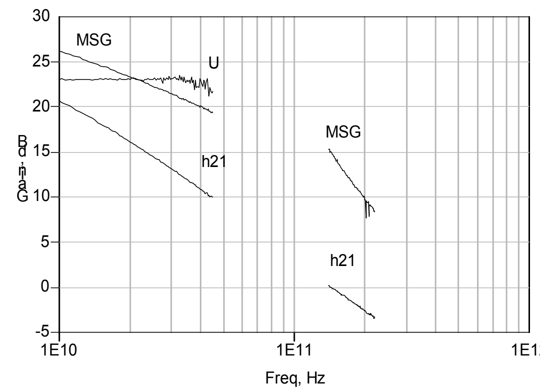

Fig. 2. Gains of 0.5 x 6 μm^2 emitter and 0.7 x 6 μm^2 collector HBT with a 300 nm collector. Bias conditions are: I_C= 3.6 mA and V_{CE} = 1.2 V.

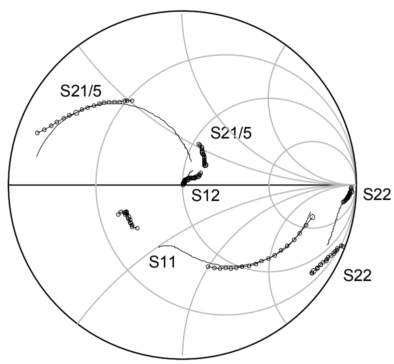

Fig. 3. Measured device S-parameters from 6-45GHz and 140-220 GHz for the transistor with a 300 nm collector. The solid line represents the equivalent circuit model derived from the low frequency measurements.

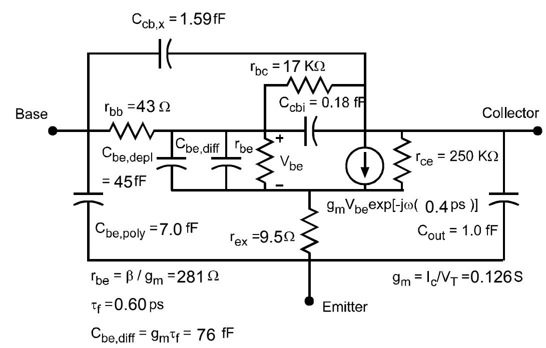

Fig. 4. Device equivalent circuit model for transistor with 300 nm collector. Bias conditions are: I_C= 3.6 mA and V_{CE} = 1.2 V.

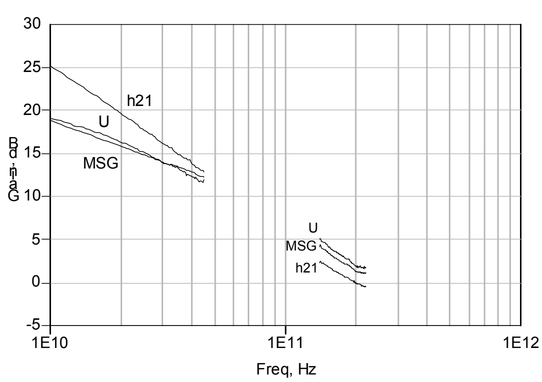

Fig. 5. Gains of 0.7 x 6 μm^2 emitter and 1.0 x 6.4 μm^2 collector HBT with a 150 nm collector. Bias conditions are: I_C= 3.0 mA and V_{CE} = 1.0 V.

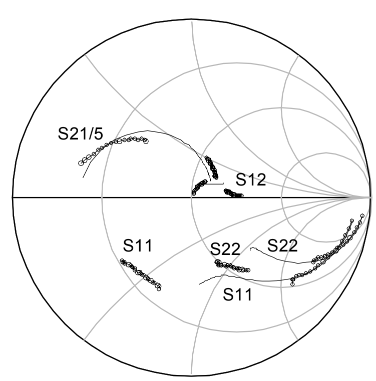

Fig. 6. Measured device S-parameters from 6-45GHz and 140-220 GHz for the transistor with a 150 nm collector. The solid line represents the equivalent circuit model derived from the low frequency measurements.