PICOSECOND OPTOELECTRONIC CHARACTERIZATION OF A HETEROJUNCTION BIPOLAR TRANSISTOR

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ABSTRACT

A time domain network analyzer with a bandwidth greater than 100 GHz was constructed using picosecond optoelectronic techniques. The S-parameters of a heterojunction bipolar transistor with an f_{max} of 35 GHz was measured using this system. The measured S-parameters agree with those obtained using a conventional automatic network analyzer over the range of frequency overlap.

I. INTRODUCTION

In recent years there has been steady progress in the development of high frequency semiconductor devices and millimeter wave integrated circuits. Current high frequency transistors have cutoff frequencies well beyond the bandwidth that can be measured conveniently using conventional network analyzers. As a result the millimeter wave S-parameters of devices most commonly are calculated from the extrapolation of the small signal models of the transistor which are based on the microwave measurements. This extrapolation method has not been proven to be reliable in predicting behavior of devices at frequencies much higher than the measured frequency. By using external mixers the current bandwidth of network analyzers has been extended to about 110 GHz. But several difficulties arise in characterization of devices in the millimeter wave region. Above 40 GHz the transistors have to be mounted in high frequency test fixtures with waveguide-to-microstrip transitions. It is difficult to design wide bandwidth and low loss waveguide-to-microstrip transitions. The actual S-parameters of the device have to be de-embedded from the test fixture and if the transitions have a high insertion loss erroneous results can be obtained. Another technique for characterization of high frequency transistors is by using a six-port network analyzer (1). In this method mixers are not used but it also requires using transitions and a complicated de-embedding procedure to obtain the actual S-parameters of the device.

Use of time-domain techniques for characterization of devices offer advantages over frequency-domain techniques used by most network analyzers. By measuring the response of the device in the time-domain and taking the Fourier transform of the data the frequency performance of the device can be calculated. The response of the device can be "windowed" in the time-domain and separated from reflections from transitions and other unwanted signals before it is analyzed. This will simplify de-embedding of the S-parameters of devices. But the use of TDNA for device characterization has been very limited due to a lack of availability of fast electrical pulse generators and oscilloscopes.

In order to improve and optimize performance of millimeter wave transistors it is important to have a simple technique for direct characterization of devices at very high frequencies. Picosecond optoelecronic techniques offer a new method for generation and sampling of ultrafast electrical pulses (2). These electrical pulses can be used to test the response of high speed semiconductor devices (3) and integrated circuits (4). Using photoconductive switches, picosecond electrical pulses can be generated and sampled at a very short distance from a device. Therefore, the high frequency signals do not have to travel through long sections of transmission lines and waveguide transitions, making this technique superior to conventional network analyzers. In this study heterojunction bipolar transistors (HBTs) (5) which are very promising devices for applications in microwave and millimeter wave integrated circuits (6) were characterized using the picosecond optoelectronic technique.

II. MEASUREMENT

An HBT was mounted in an optoelectronic test fixture as shown in figure 1. The microstrip lines were fabricated on silicon on sapphire (SOS) substrates and were designed to have a 50 Ω impedance. On each side of the device there are two photoconductive switches which consist of 25 μm gaps in the side microstrip lines. One of the switches on each side of the device is used for generation of electrical pulses and the other one for sampling of electrical pulses. Therefore, depending on which one of the four switches is used as the generator and which one as the sampler the device can be characterized completely. The SOS substrates were heavily implanted with silicon ions to shorten the carrier lifetime of the silicon epi-layer to subpicosecond levels. The center microstrip lines, in addition to being used for launching the fast electrical pulses, are also used to supply the DC biases to the transistor. This will allow the characterization of the device at any bias point.

Figure 2 shows the schematic of the picosecond optoelectronic system used to measure the S-parameters of the HBT. The train of picosecond laser pulses from the dye laser

1989 IEEE MTT-S Digest

is split into two beams. The first beam passes through an optical chopper and is focused onto one of the pulse generating switches with the chopper reference fed into the reference input of the lock-in amplifier. The second beam travels a path with a variable length and is focused onto one of the sampling switches. The length of this path can be varied very precisely by movement of a stepper motor controlled translation stage. The pathlength of the second beam can be varied such that it arrives at the sampling switch, before, during, or after the arrival of the optical pulse at the generation switch. The output from the sampling switch is fed into the input of the lock-in amplifier. Using this generation and sampling system the HBT was characterized in the time-domain. By taking the Fourier transform of the reflected and transmitted signals and normalizing it to the Fourier transform of the appropriate input signal the S-parameters of the HBT can be measured.

For comparison with the S-parameters measured by the picosecond optoelectronic technique a similar HBT was characterized by a conventional vector network analyzer (HP 8510). The HBT was mounted in a test fixture and the S-parameters of the device were de-embedded using a simple delay-thru technique over the range of 1-26 GHz.

III. RESULTS

Figure 3 shows the response of the HBT obtained by using switch 1 as the pulse generator and sampling switch 2. The first peak in the figure corresponds to the electrical autocorrelation of the input pulse to the device. The small peak after the autocorrelaion peak is due to reflection from the bond wires and the broader peak is the reflection from the device. The reflections from the bond wires and the device overlapped with the autocorrelation signal because the distance between the switches and the HBT was not long enough and the reflected signals arrived at the sampling switch before it had finished sampling the input pulse. To analyze the data the autocorrelation signal was seperated from the device reflection and the tail portion of it was approximated. By taking the ratio of the Fourier transform of the reflected signal to the autocorrelation signal the input reflection coefficient (S_{11}) of the HBT shown in figure 5(a) was calculated.

To measure the input gain of the transistor (S_{21}) switch 1 was used as the pulse generator and switch 4 as the sampler. The result shown in figure 4 shows the electrical pulse that has been broadend by passing through the transistor. By taking the Fourier transform of this pulse and normalizing it to the input signal to the transistor S_{21} of the HBT shown in figure 6(a) was calculated. A similar procedure was also used to measure S_{12} and S_{22} of the HBT.

The measured S_{11} and S_{21} of a similar HBT by a conventional network analyzer are shown in figures 5(b) and 6(b) respectively. Except for some discrepancies the two measurement techniques are relatively in good agreement. The discrepancies are believed to be due to the simple de-embedding procedure used to remove the effect of the test fixture on the network analyzer measurements, and slight differences between the two HBTs tested.

IV. CONCLUSION

S-parameters of an HBT were measured up to 40 GHz using a picosecond optoelectronic technique. The results show good agreement with measurements of a similar HBT using a conventional vector network analyzer over the bandwidth of the network analyzer (26 GHz). The optoelectronically measured S-parameters of the device were limited by the cutoff frequency of the device. The system itself has a bandwidth greater than 100 GHz and S-parameters of transistors can be measured over this frequency range. New HBTs with higher cutoff frequencies are currently being characterized. Although in this study the optical switches were fabricated on a different substrate from the device, it is possible to integrate optical switches with devices on the same wafer. This will allow on-wafer measurement of S-parameters over a wide bandwidth. But since the switches occupy a large area of the wafer, the number of test patterns will be limited. Other techniques for on wafer measurement of S-parameters are currently being investigated.

ACKNOWLEDGEMENT

This work was supported in part by TRW under the California MICRO program and in part by the Air Force Office of Scientific Research.

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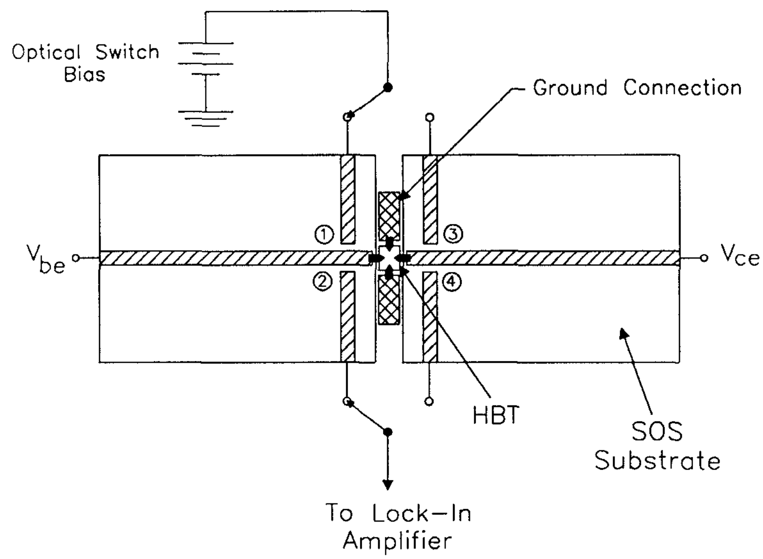

Figure 1. Picosecond optoelectronic test fixture with an HBT attached to the center microstrip lines.

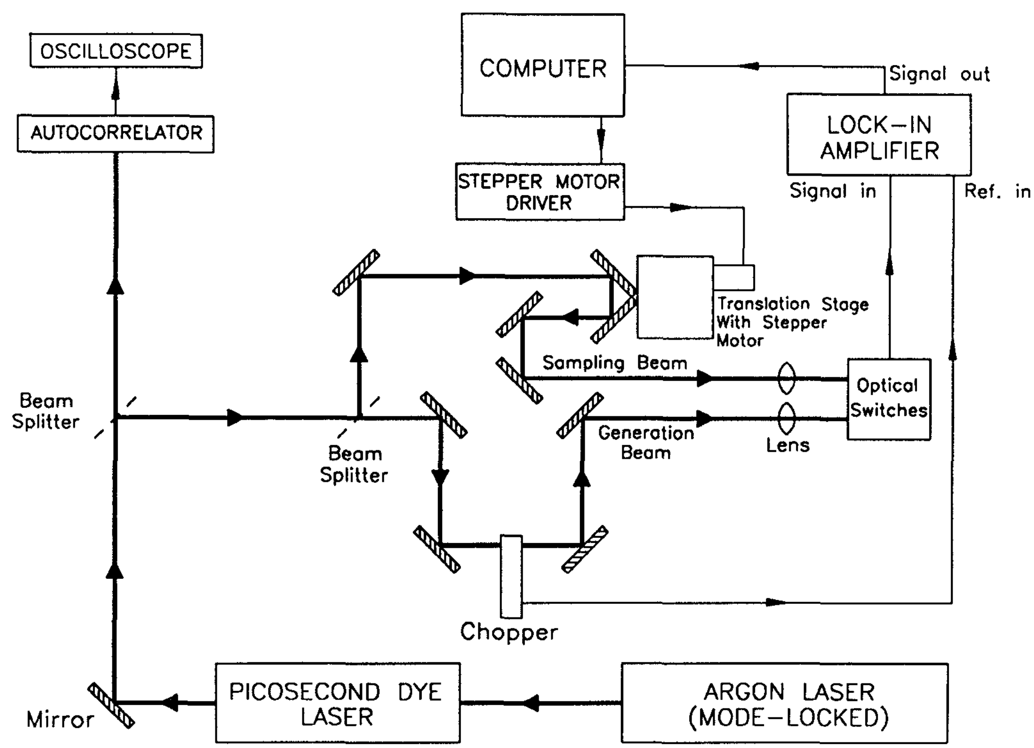

Figure 2. Experimental setup for generation and sampling of fast electrical pulses.

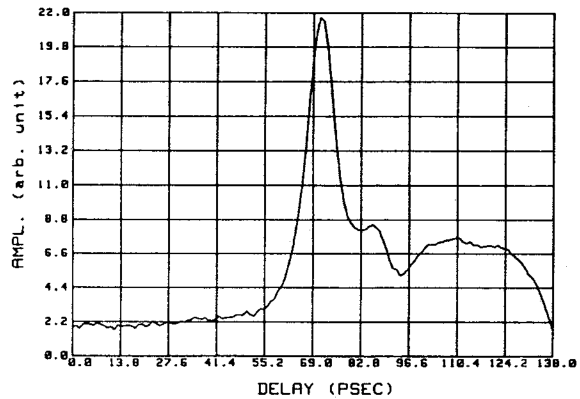

Figure 3. Input reflection measurement of the HBT by using switch 1 as the pulse generator and sampling switch 2.

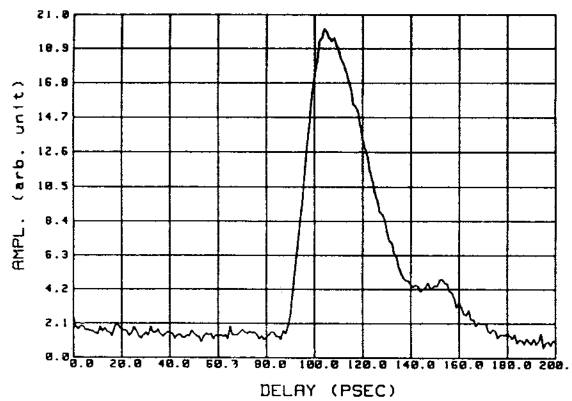

Figure 4. Forward transmission measurement of the HBT by using switch 1 as the pulse generator and sampling switch 4.

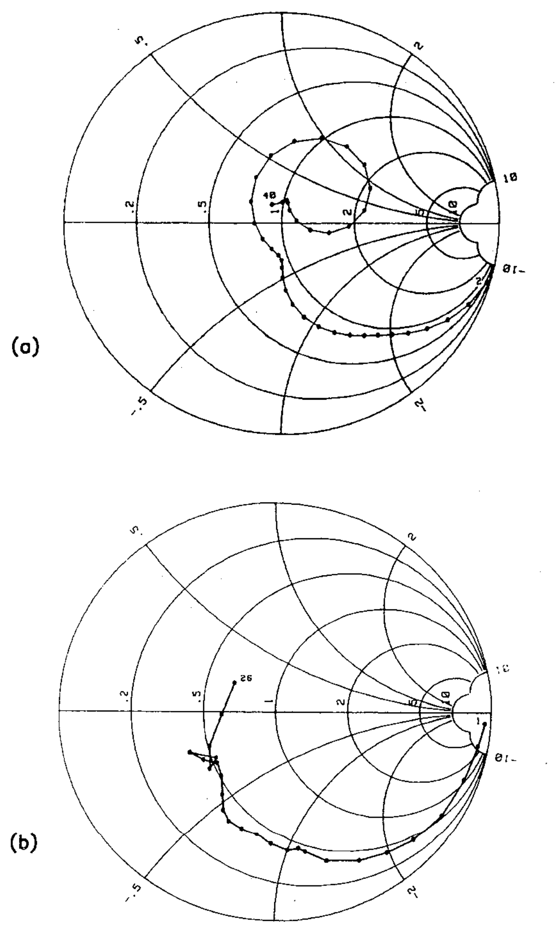

Figure 5. (a) S_{11} of the HBT from 2 to 40 GHz using the picosecond optoelectronic system.
(b) S_{11} of a similar HBT to above from 1 to 26 GHz using a conventional network analyzer.

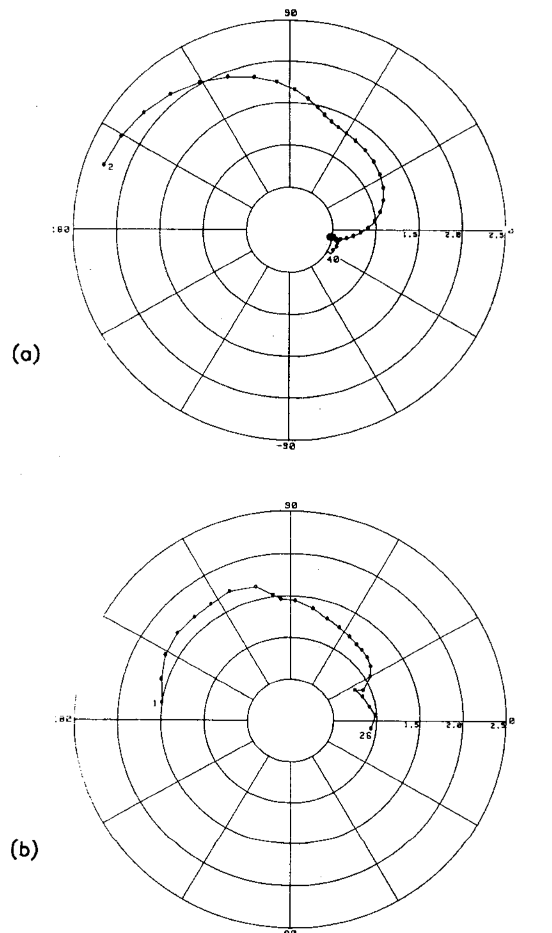

Figure 6. (a) S_{21} of the HBT from 2 to 40 GHz using the picosecond optoelectronic system.
(b) S_{21} of a similar HBT to above from 1 to 26 GHz using a conventional network analyzer.