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Picosecond Optoelectronic Measurement of *S* Parameters and Optical Response of an AlGaAs/GaAs HBT

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***Abstract* —The *S* parameters of an AlGaAs/GaAs heterojunction bipolar transistor (HBT) were measured using a picosecond optoelectronic system. The measured *S* parameters show qualitatively good agreement with those obtained using a conventional vector network analyzer. The optical response of the HBT was also measured using this system by directly illuminating the base–collector region. Used as a phototransistor, the HBT showed pulse widths with FWHM as short as 15 ps.**

I. INTRODUCTION

In recent years there has been steady progress in the development of high-frequency semiconductor devices and millimeter-wave integrated circuits. Present 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 are commonly calculated from the extrapolation of small-signal models of the transistor based on the microwave measurements. This extrapolation method has not been proven to be reliable in predicting the behavior of devices at frequencies much higher than the measured frequency. By using external mixers the present bandwidth of network analyzers has been extended to about 110 GHz. But several difficulties arise in characterizing devices in the millimeter-wave region. At high frequencies the transistors have to be mounted in 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 with transitions having a high insertion loss erroneous results can be obtained.

Use of time-domain techniques for characterization of devices offers advantages over the 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 due to transitions and other unwanted signals before it is analyzed. This will simplify de-embedding of the *S* parameters of devices. But the use of time-domain techniques 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 the performance of millimeter-wave transistors it is important to have a simple technique for direct characterization of devices at very high frequencies. Picosecond optoelectronic techniques offer a new method for generating and sampling ultrafast electrical pulses [1]–[3]. These electrical pulses can be used to test the response of high-speed semiconductor devices [4] and integrated circuits [5], [6]. 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, *S* parameters and the optical response of AlGaAs/GaAs heterojunction bipolar transistors (HBT's), which are very promising devices for applications in microwave and millimeter-wave integrated circuits [7], were characterized using picosecond optoelectronic techniques.

II. MEASUREMENT

An AlGaAs/GaAs HBT was mounted in an optoelectronic test fixture of the type shown in Fig. 1. The HBT tested had $3\times10\ \mu m^2$ emitter and self-aligned base ohmic metal. The structure and fabrication of this device were previously reported in detail [8]. The microstrip lines were fabricated using gold on silicon-on-sapphire (SOS) substrates. A thin layer of chromium was used to improve adhesion between the gold and the silicon surface. The sapphire substrates were about 125 μm thick and the microstrip lines were designed to have a 50 Ω impedance. The silicon epi-layer was about 0.5 μm thick and was heavily implanted with four different energies of silicon ions to shorten the carrier lifetime to subpicosecond levels [9].

On each side of the device there are two photoconductive switches, which consist of 25 μm gaps in the side microstrip lines. By applying a dc bias to a photoconductive switch and focusing a

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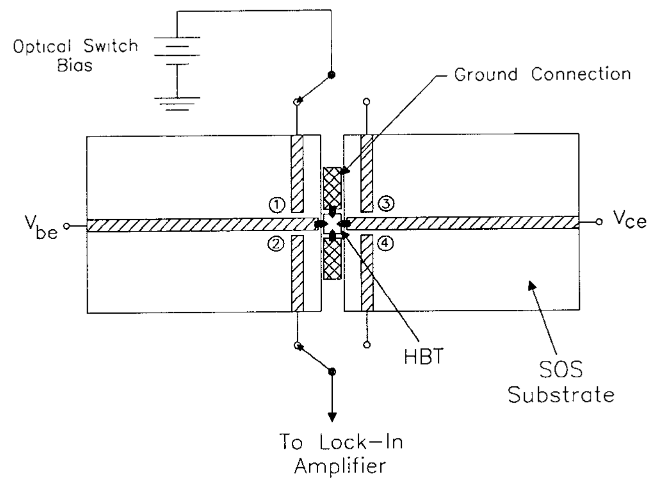

Fig. 1. Picosecond optoelectronic test fixture with an HBT wire-bonded to the center microstrip lines.

picosecond laser beam on the gap, fast electrical pulses are generated that propagate on the center transmission line. A second photoconductive switch is used for sampling the electrical pulses. The speed of the electrical pulse generated in our case is limited by the gap capacitance. The center microstrip lines, in addition to being used for launching the fast electrical pulses, are used to supply the dc biases to the transistor. This will allow the characterization of the device at any bias point. The center microstrip lines are made long enough that the reflections from the bias lines arrive at the sampling switch outside the "time window" necessary to measure the response of the device.

Fig. 2 shows the schematic of the picosecond optoelectronic system used to measure the S parameters of the HBT. The pump source for the dye laser is an actively mode-locked frequency-doubled Nd:YAG laser putting out 70 ps pulses at a wavelength of 532 nm and a repetition rate of 7.6 MHz. The dye laser uses rhodamine 6G (R6G) dye and has a cavity dumper which allows the repetition rate of the pulses to be varied. The dye laser is operated at a wavelength of 600 nm with a repetition rate of 3.8 MHz and an average power of 70 mW. The optical pulses have a pulse width of 1.2 ps measured using an optical autocorrelator. The train of picosecond laser pulses from the dye laser is split into two beams. The first beam passes through an optical chopper and is focused onto one of the pulse-generating switches on the optoelectronic test fixture. 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 moving a computer-controlled translation stage. The path length of the second beam can be varied in such a way 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. Depending on which of the four optical switches is used as the generator and which is used as the sampler, the HBT can be characterized completely 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 device can be determined [4].

III. Results

Fig. 3(a) shows the input reflection of the HBT measured 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. As the delay of the sampling pulse was varied the reflection from the bond wires and then the reflection from the device were obtained. To analyze the data, the autocorrelation signal was separated from the bond wires and device reflections. Then the reflection of the bond wires was also "windowed out." Since a 1.5 mm section of microstrip transmission line separates the device from the sampling point, the reference plane of the measurement has to be moved to account for the phase change. This can be done very simply in the time domain by time shifting the reflected signal. Dispersion of electrical pulses over this length of microstrip line was neglected [10]. 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 can be determined.

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 Fig. 3(b) shows the electrical pulse that has been broadened to about 35 ps by passing through the transistor. Again, this pulse has to be time-shifted to account for the short length of the microstrips on both sides of the device. S_{21} of the HBT can be determined by taking the Fourier transform of this pulse and normalizing it to the effective input signal from the optical switches after a calibration procedure. Similarly, the reverse transmission and output reflection of the HBT were also measured and then S_{12} and S_{22} were determined from these measurements.

The optically measured S_{21} of the HBT is shown in Fig. 4 for the frequency range of 1–40 GHz. For comparison S parameters of a similar HBT were measured using on-wafer RF probes and a conventional vector network analyzer (HP8510). The network analyzer measured S_{21} for the range of 1–26 GHz is also shown in Fig. 4. From the measured S parameters, the maximum available gain (MAG) of the device was calculated. The plot of MAG versus frequency (maximum stable gain (MSG) for conditionally stable case) for both the optoelectronic measurements and the network analyzer measurements is shown in Fig. 5. Except for some discrepancies, the two measurement techniques are in good agreement. The discrepancies are believed to be due to the effect of the bond wires on the optically measured S parameters and to slight differences between the two HBT's tested.

IV. Optical Response

HBT's are also important in applications such as high-speed optical detectors for optical communication [11] and for optical control of MMIC's [12]. As a result, it is important to measure the speed of the HBT as a photodetector. Using picosecond optoelectronic techniques the speed of photodetectors can be measured [13]. The same optoelectronic test fixture used in the S parameter measurements was used to measure the speed of the HBT as an optical detector. In this case the optical generation pulse was focused onto the HBT and the output signal was sampled at switch 4. In these measurements the base of the HBT was floating and the device was tested as a phototransistor. Since this device has a self-aligned base metal, the separation between the base fingers and the emitter edge is only about 0.15 μm [8]. As a result the laser pulse penetrates the device only between the base and the collector fingers. For a wavelength of 600 nm the penetration depth in GaAs is about 2000 Å [14]. With base and collector thicknesses of 1500 Å and 5000 Å, respectively, more than 95% of the light absorption will occur within these two layers.

The optical response of the HBT for a collector-to-emitter voltage of 3 V is shown in Fig. 6. The pulse has a FWHM of about 15 ps, which is very fast considering the device does not

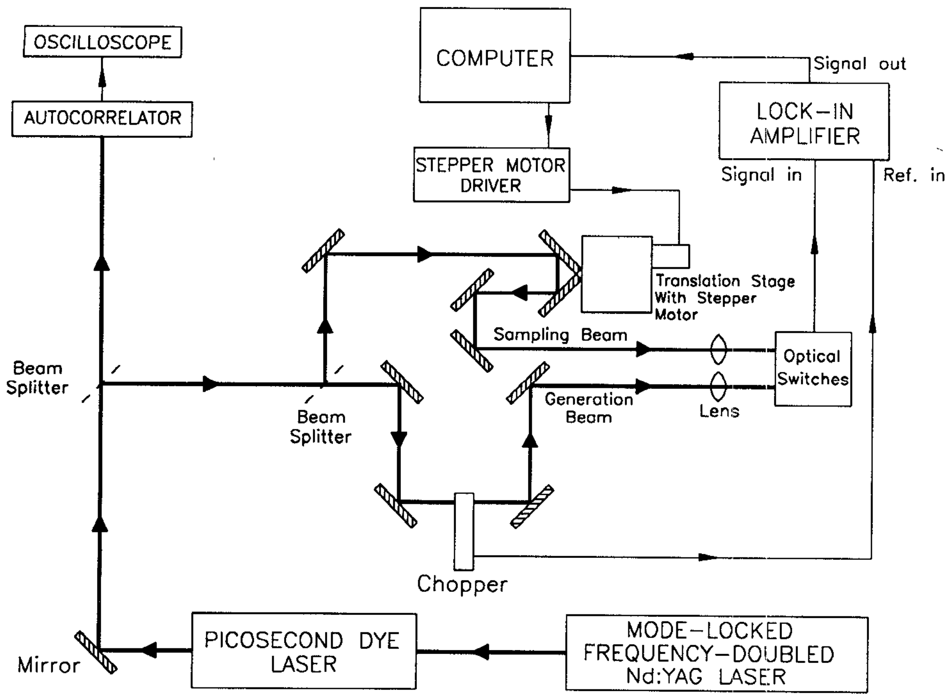

Fig. 2. Experimental setup for generation and sampling of fast electrical pulses using a computer-controlled optical time delay

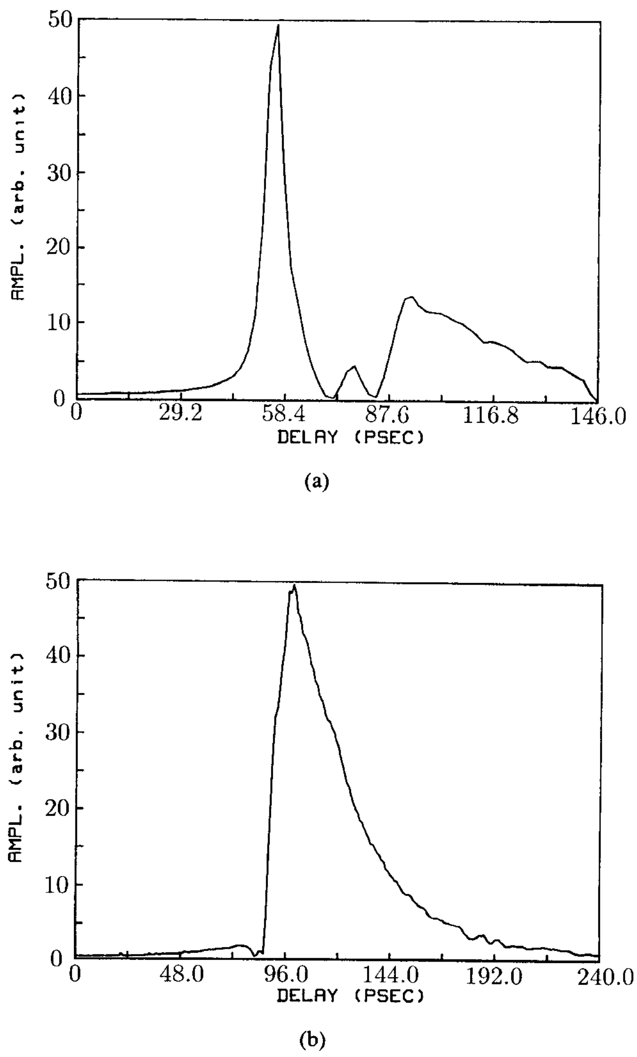

Fig. 3. (a) Input reflection measurement of the HBT using switch 1 as the pulse generator and sampling switch 2 (b) Forward transmission measurement using switch 1 as the pulse generator and sampling switch 4

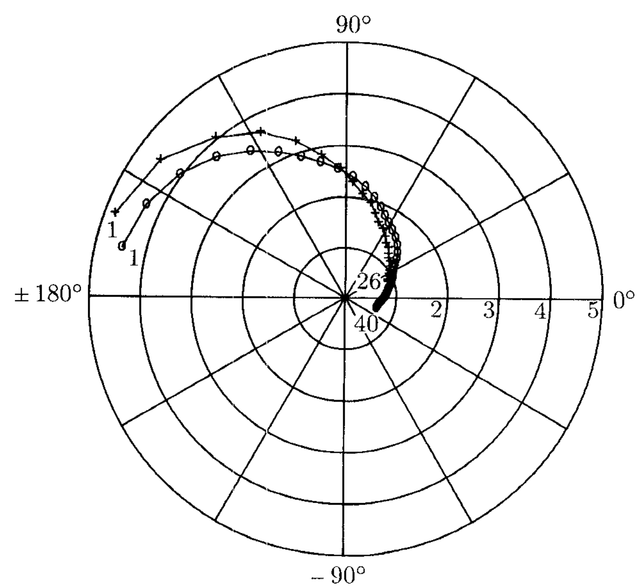

Fig 4 Comparison between optically measured S_{21} of the HBT (∘) from 1 to 40 GHz and network analyzer measurement (+) from 1 to 26 GHz

have a built-in field in the base region. The pulse width of the optical response of the HBT versus the collector-to-emitter voltage is shown in Fig. 7. As can be seen from this figure, the pulse width decreases from about 55 ps at 0 V to 15 ps at 3 V and remains constant for higher voltages. Comparing Fig. 6 with Fig. 3(b), it is observed that a much faster response time was obtained by directly injecting an optical signal into the HBT (bypassing the base input). This demonstrates that this device is intrinsically fast and that the electrical performance is limited by the base resistance.

V. Conclusion

S parameters of an HBT were measured up to 40 GHz using a picosecond optoelectronic technique. The results show qualitatively good agreement with measurements of a similar HBT using

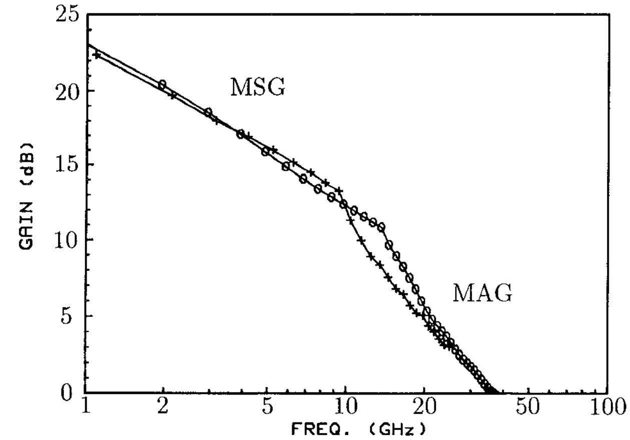

Fig 5 Maximum available gain (MAG)/maximum stable gain (MSG) versus frequency of the AlGaAs/GaAs HBT calculated from the measured S parameters by the optoelectronic system (∘) and from network analyzer measurement (+)

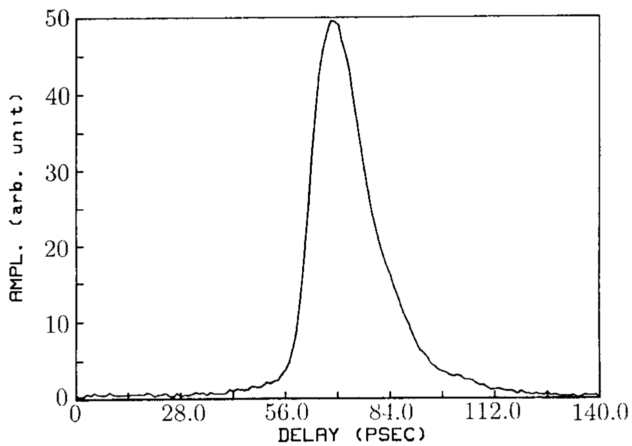

Fig 6 Optical response of the HBT used as a phototransistor for $V_{ce} = 3$ V.

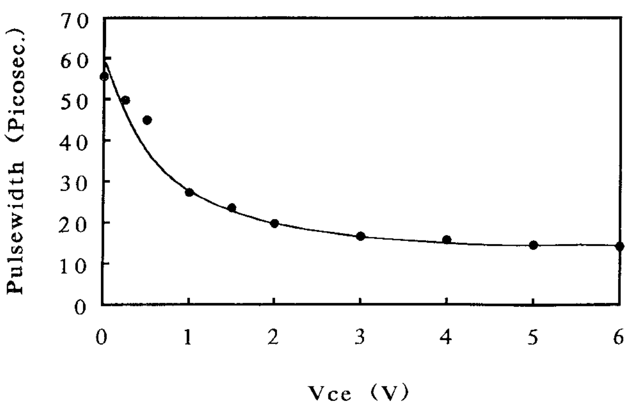

Fig 7 Variation of the optical response pulse width as a function of the collector-to-emitter voltage

on-wafer RF probes and 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 150 GHz. New HBT's with higher cutoff frequencies are currently being characterized. The optical response of the HBT was also measured using this system. HBT's appear to be very promising as high-speed optical detectors. Although in this study the optical switches were fabricated on a different substrate than the device, it is possible to integrate optical switches with devices on the same wafer and remove the effect of the bond wires on the measurements. This will allow on-wafer measurement of S parameters over a wide bandwidth.

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Control of a GaAs Monolithic *Ka*-Band Phase Shifter Using a High-Speed Optical Interconnect

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Abstract **—The use of a high-speed optical interconnect in the control of a *Ka*-band GaAs monolithic phase shifter is described. A 16 b serial control signal was used to modulate the output of a laser transmitter, and the transmitted optical signal was detected and demultiplexed into 16 parallel electrical outputs using a high-speed hybrid GaAs optoelectronic**

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