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3.C Characterization of Ultrafast Devices Using Electro-Optic Sampling

Recent advances in GaAs technology have resulted in several new classes of devices, all of which have very high-speed response.[1,2] These devices have been shown to have rise times (10–90% of peak) of tens of picoseconds,[1] which have been measured indirectly.

The indirect measurements are necessary since the fastest commercially available sampling oscilloscope has an intrinsic response time of 25 ps and jitter of a few picoseconds. One way to accomplish this measurement is by the use of a ring oscillator. Here, many devices are connected in serial with the output fed back to the input. The overall rise time of the oscillator is then equal to the rise time of a "typical" device times the number of devices in the ring. While this scheme is easy to implement, the contributions from individual devices are averaged. High-frequency gain measurements, on the other hand, can be made using cw microwave sources. Due to frequency limitations of current packaging techniques, most measurements are limited to 18 GHz.

The electro-optic sampling system[3] developed at LLE has a demonstrated response time of less than half of a picosecond.[4] The corresponding bandwidth extends into the terahertz regime, making this system very attractive for the characterization of individual devices in the picosecond regime.

As shown below, the extreme speed and bandwidth available with this system allow measurements, which yield not only information on the rise time of an individual device, but also its high-frequency gain characteristics, transit time effects, variations of gate capacitance with gate bias, etc. All of these measurements are essential for a complete understanding of these devices.

Descriptions of the sampling system have been published previously.[3,5] In this system, pairs of 100-fs pulses at 615 nm and 100-MHz repetition rate are produced by a colliding-pulse, mode-locked (CPM) laser. One pulse train is used to produce electrical transients via a Cr-doped GaAs photoconductive switch. This electrical pulse is superimposed onto a dc bias and applied to the gate of the transistor. The inverted and amplified output, superimposed on the drain bias, is then propagated along the electrodes of a $LiTaO_3$ sampling crystal. This electrical signal induces a change in the optical birefringence of the crystal, and the change is then detected with the second pulse train from the CPM laser and slow-speed photo detectors. A lock-in detection scheme, in which one of the pulse trains is chopped at an audio frequency, along with signal averaging, makes possible millivolt sensitivity for this system.

Two different sampling head geometries, shown in Fig. 22.33, have been used in these experiments. Each offers advantages to the experimenter and points out the variety of geometries available. When designing sampling heads such as these, it is essential that the response of the sampler be faster than that of the device. For devices with response times of tens of picoseconds or less, this means that commercially available connectors, which produce too much dispersion, cannot be used. In fact, the entire structure must be kept as small as possible. This minimizes the path length traveled by the high-speed signal and thus minimizes the dispersion that would otherwise be introduced into the signal.

As shown in Fig. 22.33, the Cr:GaAs switch, the device, and the sampling crystal are all as close to each other as possible. The wire bonds for high-speed input and output are kept as short as possible. In the sampler of Fig. 22.33(a), a three-wire transmission line, consisting of two ground lines and a signal line, was used. This preserved the symmetry of the MESFET geometry itself, since the two source terminals are both grounded. The geometry of the GaAs switch was chosen to allow for direct biasing of the gate of the device while keeping the actual switch as close as possible.

Figure 22.33(b) shows a schematic of the TEGFET [two-dimensional electron gas field transistor, also known as high-electron mobility transistor (HEMT), or modulation-doped field effect transistor (MODFET)] sampling head. The microstrip sampling crystal was chosen for its very high-speed response due to its very small height. Gate biasing for the TEGFET was accomplished by a very long wire bonded directly to the gate pad. The high inductance of this connection preserved the signal shape produced by the conventional microstrip GaAs switch. To date, both MESFET's (metal semiconductor field effect transistors) and TEGFET's have been tested. The MESFET response time was 25 ps, which agrees with S-parameter measurements, and the TEGFET response time of 16 ps agreed with the calculated cutoff frequency.

The experimental results shown in Fig. 22.34 demonstrate some of the measurements that can be made with the electro-optic sampling system. Figure 22.34(a) shows the TEGFET outputs for the device in the "on" and "off," or pinchoff, states. In Fig. 22.34(b) the MESFET response is shown with and without applied drain bias. Note that in all the experimental results shown, the input signal, which is capacitively coupled through the device, appears as a small negative going precursor to the

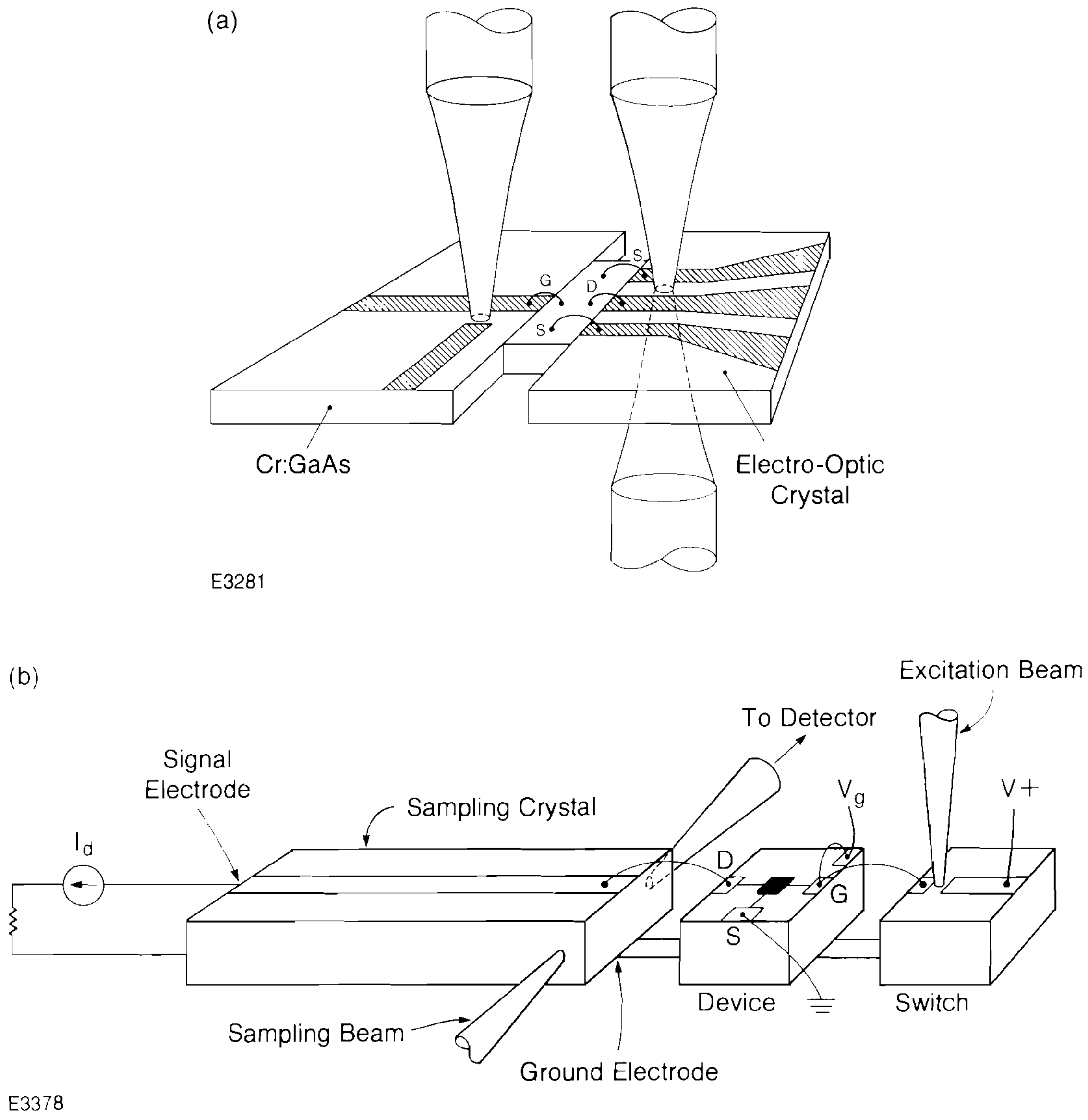

Fig. 22.33
Experimental sampling geometries used to characterize high-speed devices. (a) MESFET geometry uses photoconductive switch at right angle to gate bias line. Three-conductor transmission line on sampling crystal preserves symmetry introduced by device geometry. Flared conductors at far end of crystal preserve impedance and prevent reflections of electrical signals, while allowing sufficient width of the conductors for proper termination. (b) TEGFET sampling head uses all microstrip geometry to insure high-speed response equal to that of the device. All connections to and from the sampler were made with wire bonds. High-speed connections from photoconductive switch to the device, and from device to sampling crystal, were as short and as flat as possible in order to minimize deviations from proper high-speed transmission-line behavior. Bias lines were bonded in large vertical loops, whose large inductance would prevent degradation to the high-speed signals.

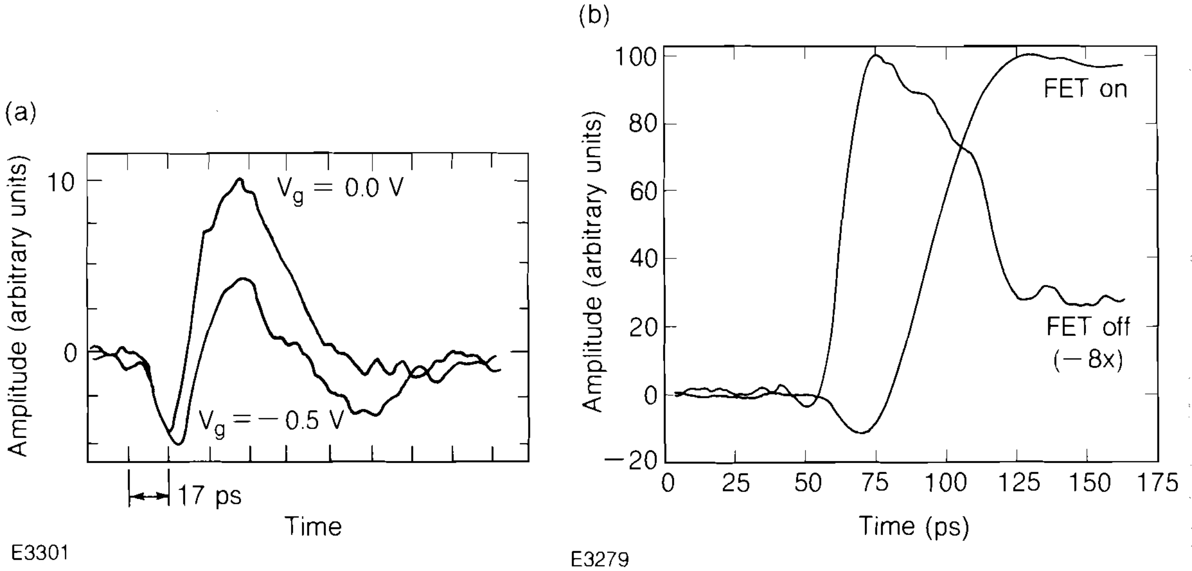

Fig. 22.34
(a) MESFET response measured with and without applied drain bias. Note that without applied bias (FET off), the curve is magnified eight times and inverted. This type of measurement yields information on transit time effects as well as rise times. (b) TEGFET response measured in the "on" (conducting, V_g = 0.0 V) and "off" (pinchoff, V_g = − 0.5 V) states. Information on gate capacitance as well as rise times are obtained in this way.

main output. This new result, only achievable using the electro-optic sampler, now makes possible measurements of the device characteristics that only become important in the picosecond regime. In the case of TEGFET's, it is known that these devices are even faster when operated in a 77°K environment.[1] This increased performance is because the electron gas experiences less scattering from the cold GaAs lattice (phonons). To extend the operating range of the sampler to this regime, a cryo-sampler is being developed. The initial version of this sampler had a response time of 16.4 ps at 4.2°K.[6] This response time was limited by needing long, dispersive cables to conduct the electrical transient from the room temperature to the cryogenic environment. By modifying the cryo-sampler to operate directly at lower, cryogenic temperatures, we have extended the operating regime of the electro-optic sampling system to encompass not only the range of two-dimensional electron gas device environments, but the entire class of superconducting devices as well.

Superconducting devices offer the potential of both very high-speed and very low-power dissipation. An all-superconducting sampler has recently been demonstrated with a 2.1-ps response time.[7] Microwatt supercomputer logic subsystems have been designed and tested.[8,9] Novel superconducting devices, such as QUITERON[10] and SMEFET,[11] offer the potential for even faster response times. The current version of the cryo-sampler has demonstrated a room-temperature response time of 1 ps. When operating at 4.2°K, the reduced dispersion of the superconducting transmission line, which connects the photoconductive switch and sampler, is expected to reduce the response time even further.

Another application of the electro-optic sampling system involves using an electrodeless sampling crystal in a reflection mode geometry, to allow access to an otherwise remote device. This geometry, reported previously, has a demonstrated response time of 0.75 ps.[12] In this technique, the optical birefringence is induced by the fringing electric field, thus eliminating the need for electrical connections between the sampling crystal and the circuit being characterized. This approach is especially attractive for more mature technologies, where more than a few devices are fabricated on a single wafer or substrate, making it impractical to allow for direct characterization of individual devices. Reflection mode sampling is currently under investigation for characterizing high-speed planar microwave structures.

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