Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 97-99 **D-2-1**

Invited

Photonic Sampling of Ultrafast Electronic Devices: Bridging the Measurement Gap

Jeremy ALLAM

Hitachi Cambridge Laboratory
Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

Today's fastest electronic devices operate at frequencies much higher than the ≈100GHz bandwidth of conventional electronic instruments. Photonic sampling using an ultrafast laser offers one way to bridge this measurement gap. We will describe an approach based on monolithic integration of ultrafast photoconductors and electronic devices. Electro-optic sampling with THz bandwidth is used to measure signals associated with passive elements (e.g. airbridges) and active devices (e.g. dual-gate FETs). An alternative approach using antenna-coupled THz beams is also proposed.

1. Introduction

The operating frequency of active semiconductor devices continues to rise towards the THz regime. For example, field effect transistors were recently reported[1] with a maximum oscillation frequency of ≈600GHz, obtained by extrapolation from conventional electronic measurement below 100GHz. Such extrapolation is unproven, and may fail at frequencies approaching the characteristic rates for transport processes. Cut-off frequencies for other types of devices, and large-signal switching times, cannot be obtained by simple extrapolation. Hence there is an increasing need for direct measurement methods in the 100GHz - 1THz range.

Optoelectronic sampling techniques based on ultrafast lasers offer improved measurement bandwidth compared with all-electronic measurement. Typically, picosecond electrical pulses are generated by illumination of photoconductive switches, and their propagation in circuits and the response of the device under test (DUT) is measured using electro-optic probing[2] with a time resolution of a few hundred fs.

The small-signal scattering parameters (S-parameters) of heterojunction FETs have been measured up to ≈100GHz,[3] using devices connected to a coplanar stripline sampling circuit using wire bonds. For higher frequencies, monolithic integration of the device with the sampling circuit is required to avoid the parasitic inductance of the wire-bond. Zeng et al.[4] reported monolithic integration of an FET with a step function generator, and measured switching times of ≈4ps. For small-signal broadband characterisation, short-pulse (quasi-delta-function) excitation is required. Hence, ultra-high-bandwidth S-parameter measurements will require monolithic integration of an ultrafast photoconductor with the device and sampling circuit.

Ultrafast sampling of electronic devices at THz frequencies will allow direct access to the dynamics of non-equilibrium (e.g. ballistic) transport, and to dynamics of quantum transport in nanostructures.

2. Monolithic integrated sampling circuit

We have reported[5), 6)] a monolithically-integrated opto-electronic circuit for ultrafast sampling of multi-terminal devices. Fig. 1 shows a schematic of the sampling circuit, showing the annealed low-temperature-grown GaAs (LT GaAs) layer on which the photoconductive switches are formed, the mesa on which the device is fabricated, interconnection of switch and device using coplanar waveguide (CPW), excitation of the photoconductive switch using a first laser pulse, and sampling of the fringing fields of the waveguide by means of an electro-optic tip probed by a second, time-delayed laser pulse.

By careful control of the epitaxial layers and annealing process, it is possible to simultaneously achieve sub-picosecond response times in the photoconductive layer and optimised properties of the device layer.[6] We have investigated in-plane-gate[5] and dual-gate[6] FETs fabricated on these layers.

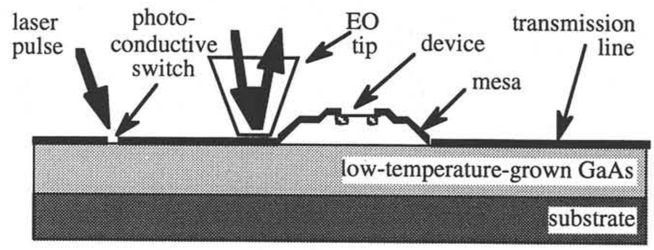

Fig. 1. Monolithic integration of LT GaAs photoconductive switch, coplanar transmission line, and device.

3. Passive elements: THz airbridges

A feature of CPW is the propagation of asymmetric slotline modes in addition to the symmetric CPW mode. Airbridges joining the CPW ground planes were shown[7] to suppress slotline modes at frequencies up to 100GHz. Here we extend the measurement range by an order of magnitude, and show suppression of slot modes up to 1THz.

Figure 2 shows the interdigitated photoconductive switch, CPW and airbridge. The asymmetric and symmetric modes were distinguished by electro-optic probing on either side of the CPW (Fig. 3). In the absence of airbridges, strong asymmetric terms were observed. Figure 4 shows the Fourier transform of the propagating pulses. The signal bandwidth is limited to ≈1THz by the -30dB noise floor, and decreases with increasing propagation distance due mainly to radiative losses. The signals measured on "same" and "opposite" sides of the CPW are almost identical, indicating suppression of the slotline mode up to 1THz by airbridges.

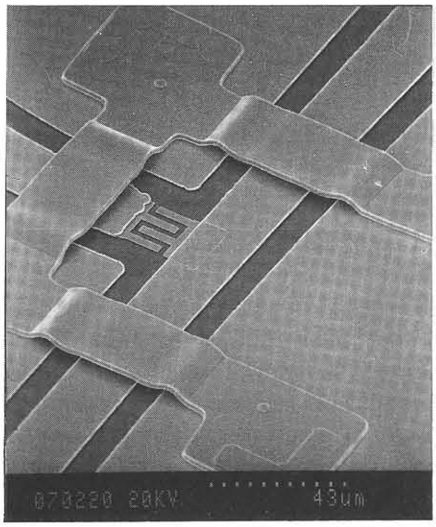

Fig. 2. Micrograph of interdigitated photoconductive switch connected to CPW. Ground planes are connected by airbridges.

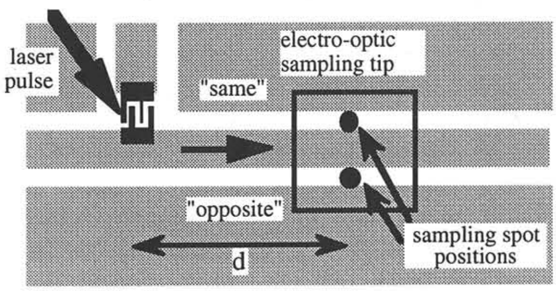

Fig. 3. Pulse generation and sampling geometry.

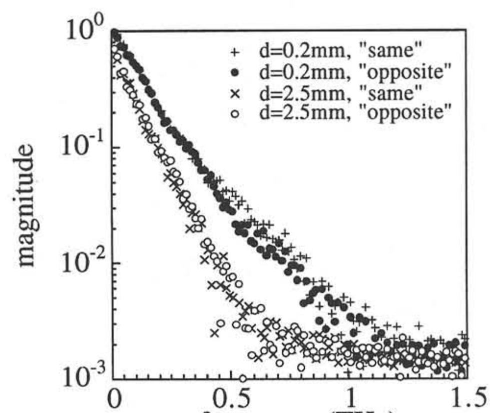

Fig. 4. Magnitude of pulse generated at photoconductive switch and sampled at distance d, shown in frequency domain. The signal is sampled at "same" and "opposite" sides of the CPW.

4. Pulse propagation through dual-gate FET

We have studied dual-gate FET's (Fig. 5) integrated with an ultrafast photonic sampling circuit,[6] and investigated picosecond pulse propagation through the gates and coupling between gates. Fig. 6 shows the incident, reflected and transmitted pulses on one of the gates. The absence of spurious reflections and features on the trailing edges is due to the use of mode-discriminating electro-optic sampling[8] which eliminates the detection of freely-propagating radiation from the photoconductive switch. The magnitude and phase of the S-parameters associated with the reflection and transmission are shown in Fig. 7. The origin of the oscillating structure in the S-parameters has not yet been clearly determined, nor has the high-frequency gain of the FET been measured due to a high contact resistance. Measurements on simpler FET structures with cut-off frequencies >100GHz are in progress.

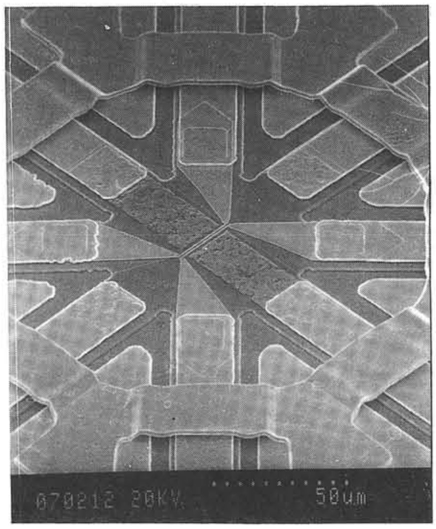

Fig. 5. Micrograph of dual-gate FET integrated into CPW sampling circuit.

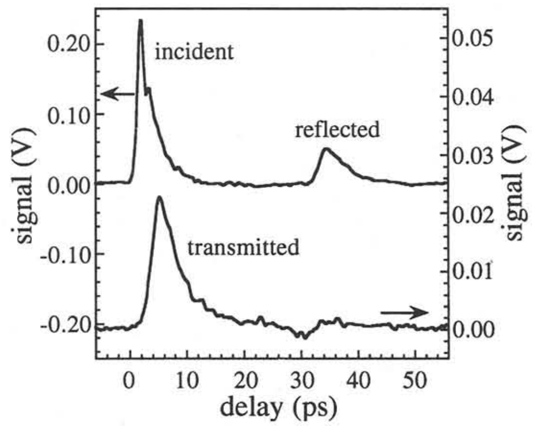

Fig. 6. Incident, reflected and transmitted voltage transients from one of the gates.

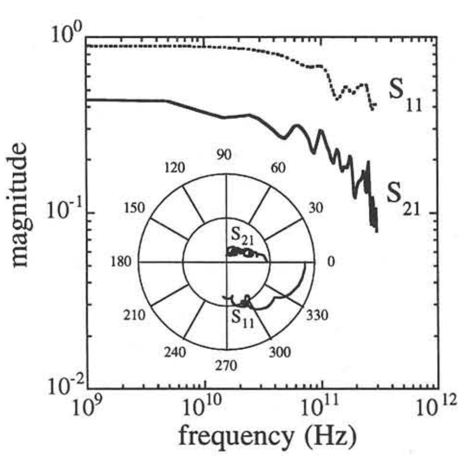

Fig. 7. Magnitude and phase (inset, polar plot) of the reflection (S_{11}) and transmission (S_{21}) parameters.

The measurement bandwidth is limited to ≈300GHz at present due to the response time of the photoconductive switch, radiative losses along the 3mm propagation distance from the photoconductive switch to the device, and the uncertainty associated with modelling the non-quasi-static pulse propagation. The bandwidth can be increased towards 1THz by optimisation of the switches and by fabricating air-spaced coplanar lines on a thin membrane,[9] although this has not yet been demonstrated in conjunction with the monolithic integrated structure discussed here.

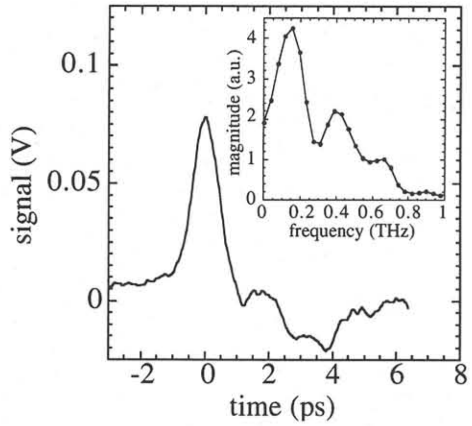

Fig 8. THz impulse detected using EO sampling.
Inset: Fourier transform of impulse.

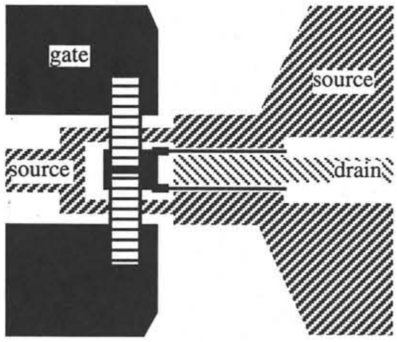

Fig. 9. Connection of twin-gate-finger FET to broad-band antenna for measurements in common-source configuration. The gates are contacted by means of an airbridge. Source-gate and drain-source transients are coupled out via CPW.

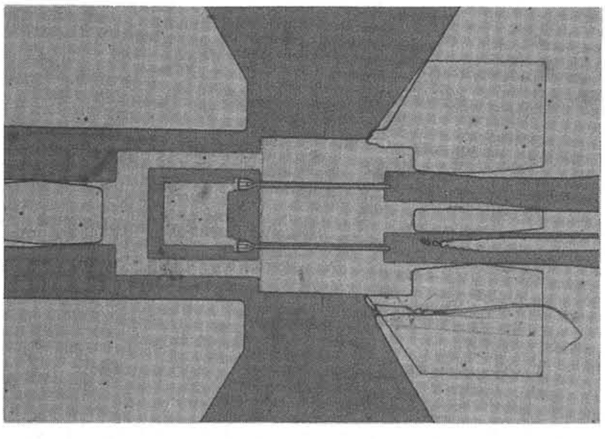

Fig. 10. Micrograph of antenna-coupled THz transistor, shown prior to fabrication of the gate-contact airbridges.

5. THz transients for device characterisation

Freely-propagating broadband THz transients can be efficiently generated using photoconductive switches coupled to planar antennae.[10] The photoconductive generation and free-space propagation of THz beams is limited neither by the carrier lifetime of the photoconductor nor by dispersion. We proposed to use antenna-coupled THz beams to stimulate a device, and electro-optic probing to measure the response, thereby avoiding the bandwidth limitations of lifetime and dispersion, as well as the need to monolithically integrate a photoconductive material with the device.

Figure 8 shows an electrical impulse generated in LT GaAs, radiated into the substrate and reflected onto a lithium tantalate electro-optic probe. The frequency content (inset) extends to ≈1THz. These initial measurements indicates that electro-optic sampling has sufficient sensitivity for the detection of THz beams. Bandwidths of several THz can be expected in optimised systems.

Figures 9 and 10 show the integration of a twin-gate-finger FET with a broadband bow-tie planar antenna. The THz transient is applied to the gate-source junction. The stimulus and response of the device are then measured by electro-optic sampling of coplanar waveguides connected to gate and drain. Direct measurement of future THz transistors appears possible using this technique.

6. Conclusions

Using a monolithic integrated optoelectronic circuit and electro-optic sampling, we have demonstrated the 1THz characterisation of passive circuit elements and S-parameter measurements up to 300GHz in device-like geometries. An alternative technique using antenna-coupled THz transients is proposed. Such techniques offer potential for direct device measurements at THz frequencies.

References

1) P. M. Smith, S.-M. J. Liu, M.-Y. Kao, P. Ho, S. C. Wang, K. H. G. Duh, S. T. Fu and P. C. Chao, IEEE Microwave and Guided Wave Letters **5** (1995) 230.
2) J. A. Valdmanis, *Semiconductors and Semimetals* **28** (Academic Press, San Diego, 1990) 135.
3) M. Y. Frankel, J. F. Whittaker and G. A. Mourou, IEEE J. Quantum Electronics **28** (1992) 2313.
4) A. Zeng, M. K. Jackson, M. Van Hove and W. de Raedt, Appl. Phys. Lett. **67** (1995) 262.
5) K. Ogawa, J. Allam, N. de B. Baynes, J. R. A. Cleaver, I. Ohbu, and T. Mishima, Appl. Phys. Lett. **66** (1995) 1228.
6) J. Allam, N. de B. Baynes, J. R. A. Cleaver, K. Ogawa, T. Mishima and I. Ohbu, Optical and Quantum Electronics (*Special Issue on Optical Probing of Ultrafast Devices*, July 1996).
7) N. H. Koster, S. Koblowsi, R. Bertenberg, S. Heinen, and I. Wolf, *Proc. 19th Euro. Microwave Conf.* (1989) 666.
8) N. de B. Baynes, J. Allam and J. R. A. Cleaver, IEEE Microwave and Guided Wave Letters **6** (March 1996).
9) H. J. Cheng, J. F. Whittaker, T. M. Weller and L. B. P. Katehi, IEEE Trans. Microwave Th. Tech. **42** (1994) 2399.
10) Ch. Fattinger and D. Grischkowsky, Appl. Phys. Lett. **54** (1989) 490.