A test system

The present invention is generally concerned with the field of test systems. More specifically those for testing the integrity of an electronic device.

Time domain reflectometers (TDRs) are used to test the integrity of cables, printed circuit boards, electronic devices and the like. They operate by transmitting a short rise time pulse through an object to be tested, usually the object is referred to as the "Device Under Test" or DUT. If the DUT has any breaks or short circuits in its wiring then the pulse will be at least partially reflected. If no defects are present and device wiring is properly terminated then the pulse will not be reflected.

It has previously been suggested to perform TDR using pulses see for example, US7280190 which uses THz transmitters and receivers built on Electro-optic sampling technology.

The present invention provides a system to perform TDR or a reflectometer which uses photoconductive elements as the receivers and generators and, in a first aspect provides a reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element.

In an embodiment. the pulses outputted by the first photoconductive element are in the frequency range from 10GHz to 10THz. In a further embodiment, the frequency range is from 50GHz to 500GHz.

The choke resistor limits the current flow after the optical excitation of the photoconducting gap at the first photoconductive element.

Pure, single-crystal optically active semiconductors typically have a charge-carrier lifetime of over 1ns (or >1μs in the case of Si or other materials with an indirect bandgap). This is too long for the measurement or generation of picosecond electrical pulses. It is known to reduce the charge carrier lifetime of such semiconductors by radiation damaging the material, ion-implantation, low-temperature growth or the embedding of other structures such a quantum dots. In this way, carrier lifetimes of under 1 picosecond are possible. However, under the application of a high electric field free charge is less effectively captured by these means. When these low lifetime materials are used to fabricate photoconductive pulse generators, it is found that the resulting pulses are not as short as would be expected from the properties of the un-biased material.

In the above embodiment, a choke resistor is used to limit the current flow in order to allow the generation of sub picosecond pulses. Thus, the need to form a semiconductor substrate with carriers which have inherently low carrier lifetimes is avoided.

In one embodiment, the choke resistor is integrated directly onto the substrate of the photoconductive device and directly adjacent to a device electrode. In another embodiment, the choke resistor is provided on another substrate and a connection to the photoconductor is made using a bond-wire, surface mount connection etc.

In an embodiment, the photoconductive elements (PCEs) are integrated with a microstrip or co-planar transmission line on a separate substrate. It is desirable to avoid backreflections from the waveguides causing artefacts in the signal from the DUT.

To at least partially address this problem, in an embodiment matching resistors are provided onto at least one of the generator and receiver such that signal incident onto the generator and/or receiver along the microstrip are substantially absorbed.

In US4896109, the photoconductive receivers are connected directly to the 50ohm

transmission line. In this configuration, it is assumed that these devices present a high impedance and hence do not perturb the signal on the line. If the transmission line were formed on a different substrate to the generator and/or receiver then the proximity of the PCEs to the microstrip would inevitably cause a change in impedance of that line and hence back-reflections would be inevitable. The systems in accordance with embodiments of the present invention minimise such problems.

The terminating resistors may be embedded resistors at the end of the transmission lines (on the microstrip circuit itself), as an alternative to fabricating them on the photoconductive devices. The terminating resistor or resistors may be used in combination with the choke resistor.

The DUT can be directly or indirectly connected to the third terminal. For example, the input to the DUT may comprise a further transmission line connected to the DUT.

Direct propagation of an electrical pulse from the generator to the receiver can occur. However, in reflectometers in accordance with embodiments of the present invention, the path length from the generator to receiver is substantially shorter than the path length from the generator to the DUT to the receiver. Therefore, there is no overlap between the two signals in the time domain, so no confusion between outward and reflected signals arises.

In an embodiment, the path length from the generator to the DUT to the receiver is at least twice the path length from the generator to the receiver.

In one embodiment, the three point transmission line arrangement is in the form a Y, known as a Y-splitter design. The design also serves to maintain a certain minimum physical separation between generator and receiver elements sufficient for the aspheric lenses used to focus the pump beam and probe beams onto the active areas of each device. i.e. the device separation must be at least equal to the diameter of the focusing lens.

In a further embodiment, the excitation beam for the generator (pump beam) and the excitation beam for the receiver (probe beam) can be angled inwards to permit a closer device spacing.

Also, devices in accordance with embodiments of the present invention seek to avoid any propagation of the generated or received pulse through the photoconductive semiconductor substrate at all. The signal is directed immediately away from the photoconductor electrode by the bond-wire to the 100 Ω microstrip track.

The above transmission line arrangement can be used in combination with the choke resistor and/or termination resistances.

In US 4896109 a linear arrangement of photoconductive devices is described located along a single transmission line. A pulse generator is found at one end of the transmission line. The receiver devices are located at measurement points along the transmission line between the generator and the DUT.

The high dielectric constant of semiconductor substrates makes the design of a 100 Ω transmission lines difficult. Co-planar designs suffer radiation loss and microstrip design requires very thin track-widths. Coupling a transmission-line on a semiconductor substrate to a co-axial line without generating a large reflection or insertion loss is also difficult.

In an embodiment of the present invention the above problems are at least partially addressed by coupling the photoconductive elements directly to microstrip waveguides formed on low-dielectric-constant (PTFE based) substrates (Taconic (RTM) TLY5 or Rogers (RTM) RO4000 are suitable examples of copper clad materials from which high-frequency transmission lines may be fabricated) with no intervening waveguide on the semiconductor. In an embodiment, the dielectric constant ε_r is 10 or less.

In an embodiment, the path length of the pump beam is varied relative to that of the probe beam or vice versa. Prior art methods for achieving this variation comprise using

a stepper-motor actuated optical delay. This approach limits the measurement rate due to the time taken to move the optical delay optics from position to position.

In one embodiment, the system comprises a so-called "fast scanning" system, where the optical delay is obtained by oscillating a glass rhomboid as described in EP 1543372. This permits a high rate of data collection. However, the length of the maximum delay obtainable by using the spinning fast-scanning solution may be insufficient for adequate characterisation of a semiconductor device. Further systems in accordance with embodiments combine a fast-scanning optical delay with a second, long-travel "slow" linear stage-based optical delay. The overall optical delay is then the sum of that from the fast and slow delays. The acquisition method involves collecting one or more fast scanned acquisition waveforms at each value of long delay position. The waveforms from each long-delay position are combined within the controlling PC to generate an overall waveform covering a much longer range than that covered by the fast-scanning delay alone. In this way, optical delays of over 150mm are obtained. This method is referred to as a "hybrid" scanning method.

US 4 896 109 describes how a DC voltage may be used to bias the pulse-generation device. Optical chopping and phase-sensitive detection has been disclosed in the literature as a means of improving the sensitivity and selectivity (w.r.t. noise) of the signal measurement system. However, optical chopping needlessly reduces the system throughput, since the signal is off for 50% of the time.

Methods in accordance with embodiments of the present invention employ an AC bias to the pulse generator. It is then possible to use phase-sensitive detection on the signal measured directly from the receiver device. The pump and probe beams remain on continuously, so the thoughput is maximised. It should be noted that the laser generates a train of sub-picosecond pulses at a repetition rate of ~ 80MHz. This is much faster than the response rate of the electronics or digital sampling system. The 80MHz is completely smoothed out by the input capacitance of the JFET pre-amplifier. Thus, the beam can be treated as continuous, from the point of view of the acquisition system. When optical chopping is used, the beam is blocked for 50% of the time, during which time the optical power is, in effect, wasted. Using AC bias modulation avoids wasting any optical power.

Receivers of the type used in embodiments of the present invention typically have a rather high source impedance of ~ Mohm. In embodiments which comprise a pre-amplifier to amplify the output signal of the receiver, the pre-amplifier preferably has a high input impedance to measure this signal source. The input impedance of the pre-amplifier is determined primarily by its input capacitance. Using a JFET buffer, an input capacitance of ~ 5pF is provided.

In a further embodiment, for an impedance of 1Mohm, a bias frequency of

$$f = \frac{1}{2\,pi\,Z\,C} = 31.8\,KHz$$

Where C=5pF and Z=1Mohm.

This allows the optimum bias frequency for the system to be determined. At higher frequencies, the input capacitance of the JFET presents a lower impedance to the source, so reducing the signal amplitude. At lower frequencies, a longer signal integration time is necessary for the phase-sensitive detection, so limiting the measurement rate.

US4896109, Fig. 2, item 33 mentions an inductor which is used as RF-choke. Further, no integration with the photoconductor was described.

In systems in accordance an embodiment of the present invention a resistor is used. The resistor may have impedance which is constant with respect to frequency, such that it retains it's current blocking action at low frequencies. In an embodiment, the impedance should remain high for frequencies down to (1 / recombination time) for charge carriers in the photoconductor. In GaAs, the recombination time is ~ 1ns, thus, in an embodiment the choke impedance must remain high for frequencies down to 1 GHz or so. In an embodiment, the impedance is least 100,000 ohm at the AC bias frequency.

In embodiments of the present invention, an optical fibre is used to provide optical excitation to the photoconductive devices. In specific embodiments, single mode fibres are used. The fibres may also be dispersion compensated to nullify the effect of dispersion of the pulse as it passes through the fibres. Polarisation-maintaining fibres may also be used to avoid fluctuations in the signal due to motion of the fibres.

In some embodiments of the present invention the photoconductive devices are coupled to the waveguides using wire-bonding. The bond-wire has an inductance which limits the bandwidth of the signal thus this inductance should preferably be minimised. For this reason, wedge bonding method is preferable over ball bonding. Ribbon bonding is an even more preferable means of minimising the inductance of this connection. Ribbon bonding is preferable to wire-bonding, because ribbon has a lower inductance than wire. Wedge bonding is the normal method of making a ribbon bond (as opposed to ball-bonding, which is generally used with circular cross-section wire).

In an embodiment, the substrate of the photoconductive material is annealed. The substrate may be GaAs, InP, GaInAs or another III-V alloys.

Photoconductive devices generally have a smooth roll-off at their high-frequency limit. This means that although the majority of the generated and detected power lies in the <70GHz region, there is a small quantity of signal power are frequencies above this. The high dynamic range of the system means that this very high frequency content to the signal may be used to improve the risetime of the system over that obtained using the raw measured pulse.

In an embodiment, optical coupling is made using a collimated free-space beam (i.e. the devices are not coupled to the fibres using a fixed pig-tail arrangement) with two alignment mirrors used to tune the optical alignment onto the devices. This means the device-block (comprising the generator and receiver PCEs, the Y-splitter and the "spark plug" microstrip-to-coax connector) can be easily replaced.

In an embodiment, the current through the generator device as a means of characterising its performance is measured. Should ESD damage to the generator occur, the photocurrent through the generator changes.

In a further embodiment, a test signal is injected into the ground connection to the receiver device which is coupled through to the detection signal when the receiver photoconductor is illuminated by the baser beam. The size of this test-signal provides an indication as to the performance of the receiver device.

Using the above two test methods, it is possible to check for changes in the state of either device due to ESD damage or other degradation.

Systems in accordance with the above embodiments can be adapted for a variety of uses such as:

1. Fault Analysis tool – which probes a single pair of pins on a device. Manual positioning is used.
2. Quality Assurance tool – this is a semi-automated tool for testing a significant sample from a batch of IC substrates.
3. High Volume Manufacture – this is a high-throughput system to test every packages before it is integrated with the die.

The highly parallelisable architecture may require planar light circuits (PLC) which distribute the supplied optical power to many pulse generators / receivers. In a further embodiment, a Fault Analysis tool (FA-tool) would be based on a 1.55um fibre laser. Such a system may further comprise a fibre-based rapid-scan delay line and a "U" bench linear delay, to avoid the need for an optical bench or casting.

In a second aspect, the present invention provides a method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element.

~~directing the pulse from the first photoconductive element to a device under test and directing~~ the pulse reflected from the device under test to the second photoconductive ~~element~~ using a transmission line,

wherein at least one photoconductive element comprises an pair of electrodes provided on the first surface of a first substrate and said transmission line arrangement is provided on a second surface of a second ~~substrate~~,

the first and second surfaces being provided facing one another such that there is ~~communication of a pulse between the said element and the transmission line arrangement.~~

The present invention will now be described with reference to the following non-limiting embodiments in which:

Figure 1 is a schematic of a reflectometer;

Figure 2 is a detailed schematic of a reflectometer in accordance with an embodiment of the present invention;

Figure 3 is a further detailed schematic of a reflectometer in accordance with an embodiment of the present invention showing the probe of the reflectometer of figure 2, figure 3a is a schematic of a variation of the microstrip transmission line used in the reflectometer of figures 2 and 3;

Figure 4 is a schematic of a reflectometer in accordance with an embodiment of the present invention showing the photoconductive elements provided on a different substrate to the transmission lines;

Figure 5 is a schematic of a photoconductive element and transmission line for use in a reflectometer in accordance with an embodiment of the present invention;

Figure 6 is a 3D schematic of a reflectometer in accordance with an embodiment of the present invention;

Figure 7 shows an enlarged section of the schematic of figure 6;

Figure 8 is a schematic showing a bonding connection between a microstrip and photoconductive element;

CLAIMS:

1. A reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element.

2. A reflectometer according to claim 1, wherein the path length from the first photoconductive element to the second photoconductive element is substantially shorter than the path length from the first photoconductive element to the device to the second photoconductive element.

3. A reflectometer according to any preceding claim, wherein the transmission line arrangement is provided on a substrate with a maximum dielectric constant of 10.

4. A reflectometer according to any preceding claim, wherein the first photoconductive element is an generator which receives a pump beam of radiation and the second photoconductive element is a receiver which receives a probe beam of radiation, the pump beam and probe beam being emitted from the same source, the reflectometer further comprising a delay line configured to vary the path length of the pump beam is varied relative to that of the probe beam or vice versa.

5. A reflectometer according to claim 4, wherein the delay line comprises a fast scanning delay section and a slow scanning delay section, wherein said fast scanning delay section is provided by an oscillating rhomboid and said slow scanning delay section comprises a linear delay line.

6. A reflectometer according to any preceding claim, wherein the first photoconductive element is configured as a generator and the second photoconductive element is configured as a receiver, the reflectometer further comprising an AC bias unit to provide an AC bias to said generator and a phase sensitive detection unit configured to perform phase-sensitive detection on the signal measured directly from the receiver device.

7. A reflectometer according to any preceding claim, wherein said second photoconductive element is configured as a receiver, the reflectometer further comprising an amplifier to amplify the output of the receiver and unit configured to provide an input AC impedance of at least 100,000 ohm at the AC bias frequency to said amplifier.

8. A reflectometer according to claim 1, wherein photoconductive elements are coupled to the transmission line arrangement by wire bonds or ribbon bonds.

9. A reflectometer according to any preceding claim, wherein the photoconductive elements comprise GaAs, InP, GaInAs or another III-V alloys.

10. A method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element.

A Test System

The present invention is generally concerned with the field of test systems. More specifically those for testing the integrity of an electronic device.

Time domain reflectometers (TDRs) are used to test the integrity of cables, printed circuit boards, electronic devices and the like. They operate by transmitting a short rise time pulse through an object to be tested, usually the object is referred to as the "Device Under Test" or DUT. If the DUT has any breaks or short circuits in its wiring then the pulse will be at least partially reflected. If no defects are present and device wiring is properly terminated then the pulse will not be reflected.

It has previously been suggested to perform TDR using pulses see for example, US7280190 which uses THz transmitters and receivers built on Electro-optic sampling technology.

The present invention provides a system to perform TDR or a reflectometer which uses photoconductive elements as the receivers and generators and, in a first aspect, the present invention provides a reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element; and
a termination resistance provided for said transmission line configured to match the impedance of the transmission line.

In an embodiment. the pulses outputted by the first photoconductive element are in the frequency range from 10GHz to 10THz. In a further embodiment, the frequency range is from 50GHz to 500GHz.

In an embodiment, the photoconductive elements (PCEs) are integrated with a microstrip or co-planar transmission line on a separate substrate. It is desirable to avoid back reflections from the waveguides causing artefacts in the signal from the DUT.

To at least partially address this problem, in an embodiment matching resistors are provided onto at least one of the generator and receiver such that signal incident onto the generator and/or receiver along the microstrip are substantially absorbed.

In US4896109, the photoconductive receivers are connected directly to the 50ohm transmission line. In this configuration, it is assumed that these devices present a high impedance and hence do not perturb the signal on the line. If the transmission line were formed on a different substrate to the generator and/or receiver then the proximity of the PCEs to the microstrip would inevitably cause a change in impedance of that line and hence back-reflections would be inevitable. The systems in accordance with embodiments of the present invention minimise such problems.

The terminating resistors may be embedded resistors at the end of the transmission lines (on the microstrip circuit itself), as an alternative to fabricating them on the photoconductive devices.

In a second aspect, the present invention provides a reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element towards the device under test and to direct the pulse reflected from the device under test towards the second photoconductive element, said transmission line having a three terminal arrangement with the first and second elements provided at separate terminals and an input to the device provided at the third terminal.

The DUT can be directly or indirectly connected to the third terminal. For example, the input to the DUT may comprise a further transmission line connected to the DUT.

Direct propagation of an electrical pulse from the generator to the receiver can occur. However, in reflectometers in accordance with embodiments of the present invention, the path length from the generator to receiver is substantially shorter than the path length from the generator to the DUT to the receiver. Therefore, there is no overlap between the two signals in the time domain, so no confusion between outward and reflected signals arises.

In an embodiment, the path length from the generator to the DUT to the receiver is at least twice the path length from the generator to the receiver.

In one embodiment, the three point transmission line arrangement is in the form a Y, known as a Y-splitter design. The design also serves to maintain a certain minimum physical separation between generator and receiver elements sufficient for the aspheric lenses used to focus the pump beam and probe beams onto the active areas of each device. i.e. the device separation must be at least equal to the diameter of the focusing lens.

In a further embodiment, the excitation beam for the generator (pump beam) and the excitation beam for the receiver (probe beam) can be angled inwards to permit a closer device spacing.

Also, devices in accordance with embodiments of the present invention seek to avoid any propagation of the generated or received pulse through the photoconductive semiconductor substrate at all. The signal is directed immediately away from the photoconductor electrode by the bond-wire to the 100 Ω microstrip track.

The above transmission line arrangement can be used in combination with the termination resistances.

In a third aspect, the present invention provides a reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element,

wherein at least one photoconductive element comprises an pair of electrodes provided on the first surface of a first substrate and said transmission line arrangement is provided on a second surface of a second substrate,

the first and second surfaces being provided facing one another such that there is communication of a pulse between the said element and the transmission line arrangement.

The above arrangement is a flip-chip arrangement where the top face of the photoconductor is placed face down on to the microstrip circuit. Flipchip mounting can also be used to couple the photoconductors to co-planar waveguides, as well as microstrip/stripline waveguides. The electrical connection between the photo-conductive element and the microstrip is formed using one of the normal flipchip methods:

– reflow soldering

– conductive epoxy

In the case of a reflow solder process, solder paste is deposited onto the contact pads on the microstrip PCB using stencil printing or some other deposition method. The chip is placed face-down onto the PCB such that the paste contacts both the chip and the PCB. The assembly is then heated in an over to melt the solder which forms the join between the two.

The method using conductive epoxy is similar, but lower temperatures can be used for the epoxy to cure.

In order to optically excite the photoconductors in this flip-chip geometry, it is necessary to provide a small hole (for example, using a drill such as a laser-drill) in the PCB to provide optical access to the active region of the photoconductor through the PCB assembly.

An alternative method of providing optical access to the photoconductor is to fabricate the photoconductive layer on a transparent substrate. This is possible using epitaxial liftoff methods to transfer a 1μm epilayer from a GaAs wafer onto a fused quartz wafer.

In a further embodiment, a reflectometer system is provided comprising a plurality of reflectometers, wherein a single common first substrate is provided for the plurality of reflectometers such that the photoconductive elements for a plurality of reflectometers are flip chip bonded at the same time.

The above provides a multi-channel TDR system where many photoconductive elements are formed on a single semiconductor die and this die is flip-chip mounted to a microware PCB circuit which conveys the pulses to/from the various test-point on the device-under-test (typically a multi-pin IC).

In US 4896109 a linear arrangement of photoconductive devices is described located along a single transmission line. A pulse generator is found at one end of the transmission line. The

receiver devices are located at measurement points along the transmission line between the generator and the DUT.

The high dielectric constant of semiconductor substrates makes the design of a 100 Ω transmission lines difficult. Co-planar designs suffer radiation loss and microstrip design requires very thin track-widths. Coupling a transmission-line on a semiconductor substrate to a co-axial line without generating a large reflection or insertion loss is also difficult.

In an embodiment of the present invention the above problems are at least partially addressed by coupling the photoconductive elements directly to microstrip waveguides formed on low-dielectric-constant (PTFE based) substrates (Taconic TLY5 or Rogers RO4000 are suitable examples of copper clad materials from which high-frequency transmission lines may be fabricated) with no intervening waveguide on the semiconductor. In an embodiment, the dielectric constant ε_r is 10 or less.

In an embodiment, the path length of the pump beam is varied relative to that of the probe beam or vice versa. Prior art methods for achieving this variation comprise using a stepper-motor actuated optical delay. This approach limits the measurement rate due to the time taken to move the optical delay optics from position to position.

In one embodiment, the system comprises a so-called "fast scanning" system, where the optical delay is obtained by oscillating a glass rhomboid as described in EP 1543372. This permits a high rate of data collection. However, the length of the maximum delay obtainable by using the spinning fast-scanning solution may be insufficient for adequate characterisation of a semiconductor device. Further systems in accordance with embodiments combine a fast-scanning optical delay with a second, long-travel "slow" linear stage-based optical delay. The overall optical delay is then the sum of that from the fast and slow delays. The acquisition method involves collecting one or more fast scanned acquisition waveforms at each value of long delay position. The waveforms from each long-delay position are combined within the controlling PC to generate an overall waveform covering a much longer range than that covered by the fast-scanning delay alone. In this way, optical delays of over 150mm are obtained. This method is referred to as a "hybrid" scanning method.

US 4 896 109 describes how a DC voltage may be used to bias the pulse-generation device. Optical chopping and phase-sensitive detection has been disclosed in the literature as a means of improving the sensitivity and selectivity (w.r.t. noise) of the signal measurement system.

However, optical chopping needlessly reduces the system throughput, since the signal is off for 50% of the time.

In a fourth aspect, the present invention provides reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element.

The choke resistor limits the current flow after the optical excitation of the photoconducting gap at the first photoconductive element.

Pure, single-crystal optically active semiconductors typically have a charge-carrier lifetime of over 1ns (or >1μs in the case of Si or other materials with an indirect bandgap). This is too long for the measurement or generation of picosecond electrical pulses. It is known to reduce the charge carrier lifetime of such semiconductors by radiation damaging the material, ion-implantation, low-temperature growth or the embedding of other structures such a quantum dots. In this way, carrier lifetimes of under 1 picosecond are possible. However, under the application of a high electric field free charge is less effectively captured by these means. When these low lifetime materials are used to fabricate photoconductive pulse generators, it is found that the resulting pulses are not as short as would be expected from the properties of the un-biased material.

In the above embodiment, a choke resistor is used to limit the current flow in order to allow the generation of sub picosecond pulses. Thus, the need to form a semiconductor substrate with carriers which have inherently low carrier lifetimes is avoided.

The above described terminating resistor or resistors may be used in combination with the choke resistor. The above described transmission line arrangement can be used in combination with the choke resistor and/or termination resistances.

In one embodiment, the choke resistor is integrated directly onto the substrate of the photoconductive device and directly adjacent to a device electrode. In another embodiment, the choke resistor is provided on another substrate and a connection to the photoconductor is made using a bond-wire, surface mount connection etc.

Methods in accordance with embodiments of the present invention employ an AC bias to the pulse generator. It is then possible to use phase-sensitive detection on the signal measured directly from the receiver device. The pump and probe beams remain on continuously, so the throughput is maximised. It should be noted that the laser generates a train of sub-picosecond pulses at a repetition rate of ~ 80MHz. This is much faster than the response rate of the electronics or digital sampling system. The 80MHz is completely smoothed out by the input capacitance of the JFET pre-amplifier. Thus, the beam can be treated as continuous, from the point of view of the acquisition system. When optical chopping is used, the beam is blocked for 50% of the time, during which time the optical power is, in effect, wasted. Using AC bias modulation avoids wasting any optical power.

Receivers of the type used in embodiments of the present invention typically have a rather high source impedance of ~ 1 Mohm. In embodiments which comprise a pre-amplifier to amplify the output signal of the receiver, the pre-amplifier preferably has a high input impedance to measure this signal source. The input impedance of the pre-amplifier is determined primarily by its input capacitance. Using a JFET buffer, an input capacitance of ~ 5pF is provided.

In a further embodiment, for an impedance of 1Mohm, a bias frequency of

$$f = \frac{1}{2\,pi\,Z\,C} = 31.8\,KHz$$

Where C=5pF and Z=1Mohm.

This allows the optimum bias frequency for the system to be determined. At higher frequencies, the input capacitance of the JFET presents a lower impedance to the source, so reducing the signal amplitude. At lower frequencies, a longer signal integration time is necessary for the phase-sensitive detection, so limiting the measurement rate.

US4896109, Fig. 2, item 33 mentions an inductor which is used as RF-choke. Further, no integration with the photoconductor was described.

In systems in accordance with an embodiment of the present invention a resistor is used. The resistor may have impedance which is constant with respect to frequency, such that it retains its current blocking action at low frequencies. In an embodiment, the impedance should remain high for frequencies down to (1 / recombination time) for charge carriers in the photoconductor. In GaAs, the recombination time is ~ 1ns, thus, in an embodiment the choke impedance must remain high for frequencies down to 1 GHz or so. In an embodiment, the impedance is least 100,000 ohm at the AC bias frequency.

In embodiments of the present invention, an optical fibre is used to provide optical excitation to the photoconductive devices. In specific embodiments, single mode fibres are used. The fibres may also be dispersion compensated to nullify the effect of dispersion of the pulse as it passes through the fibres. Polarisation-maintaining fibres may also be used to avoid fluctuations in the signal due to motion of the fibres.

In some embodiments of the present invention the photoconductive devices are coupled to the waveguides using wire-bonding. The bond-wire has an inductance which limits the bandwidth of the signal thus this inductance should preferably be minimised. For this reason, wedge bonding method is preferable over ball bonding. Ribbon bonding is an even more preferable means of minimising the inductance of this connection. Ribbon bonding is preferable to wire-bonding, because ribbon has a lower inductance than wire. Wedge bonding is the normal method of making a ribbon bond (as opposed to ball-bonding, which is generally used with circular cross-section wire).

In an embodiment, the substrate of the photoconductive material is annealed. The substrate may be GaAs, InP, GaInAs or another III-V alloys.

Photoconductive devices generally have a smooth roll-off at their high-frequency limit. This means that although the majority of the generated and detected power lies in the <70GHz region, there is a small quantity of signal power are frequencies above this. The high dynamic range of the system means that this very high frequency content to the signal may be used to improve the rise time of the system over that obtained using the raw measured pulse.

In an embodiment, optical coupling is made using a collimated free-space beam (i.e. the devices are not coupled to the fibres using a fixed pig-tail arrangement) with two alignment mirrors used to tune the optical alignment onto the devices. This means the device-block

(comprising the generator and receiver PCEs, the Y-splitter and the "spark plug" microstrip-to-coax connector) can be easily replaced.

In an embodiment, the current through the generator device as a means of characterising its performance is measured. Should ESD damage to the generator occur, the photocurrent through the generator changes.

In a further embodiment, a test signal is injected into the ground connection to the receiver device which is coupled through to the detection signal when the receiver photoconductor is illuminated by the baser beam. The size of this test-signal provides an indication as to the performance of the receiver device.

Using the above two test methods, it is possible to check for changes in the state of either device due to ESD damage or other degradation.

Systems in accordance with the above embodiments can be adapted for a variety of uses such as:

1. Fault Analysis tool – which probes a single pair of pins on a device. Manual positioning is used.
2. Quality Assurance tool – this is a semi-automated tool for testing a significant sample from a batch of IC substrates.
3. High Volume Manufacture – this is a high-throughput system to test every package before it is integrated with the die.

The highly parallelisable architecture may require planar light circuits (PLC) which distribute the supplied optical power to many pulse generators / receivers. In a further embodiment, a Fault Analysis tool (FA-tool) would be based on a 1.55um fibre laser. Such a system may further comprise a fibre-based rapid-scan delay line and a "U" bench linear delay, to avoid the need for an optical bench or casting.

In a fifth aspect, the present invention provides a method of performing a reflectometry test on a device, the method comprising:

providing a source of pulsed radiation;

providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;

providing a choke resistor arranged such that said first photoconductive element is biased through said choke resistor, said choke resistor having a resistance of at least 100Ω;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element.

In a sixth aspect, the present invention provides a method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element using a transmission line; and
providing a termination resistance provided for said transmission line configured to match the impedance of the transmission line.

In a seventh aspect, the present invention provides a method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;
directing a pulse from the first photoconductive element to a device under test and directing a pulse reflected from the device under test to the second photoconductive element using a transmission line, said transmission line having a three terminal arrangement with the first and second elements provided at separate terminals and an input to the device provided at the third terminal.

In an eighth aspect, the present invention provides a method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;

CLAIMS:

1. A reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element; and
a termination resistance provided for said transmission line configured to match the impedance of the transmission line.

2. A reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element, said transmission line having a three terminal arrangement with the first and second elements provided at separate terminals and an input to the device provided at the third terminal.

3. A reflectometer for allowing a test of a device, the reflectometer comprising:
a source of pulsed radiation;
a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
a second photoconductive element configured to receive a pulse;
a transmission line arrangement configured to direct the pulse from the first photoconductive element to the device under test and to direct the pulse reflected from the device under test to the second photoconductive element,
wherein at least one photoconductive element comprises an pair of electrodes provided on the first surface of a first substrate and said transmission line arrangement is provided on a second surface of a second substrate,

the first and second surfaces being provided facing one another such that there is communication of a pulse between the said element and the transmission line arrangement.

4. A reflectometer according to any preceding claim, wherein the path length from the first photoconductive element to the second photoconductive element is substantially shorter than the path length from the first photoconductive element to the device to the second photoconductive element.

5. A reflectometer according to claim 2, wherein the three point transmission line arrangement is in the form of a Y or a V.

6. A reflectometer according to claim 2, wherein the three point transmission line comprises a Wye or Delta splitter.

7. A reflectometer according to any preceding claim, wherein the transmission line arrangement is provided on a substrate with a maximum dielectric constant of 10.

8. A reflectometer according to claim 1, wherein the terminating resistor is separated from the photoconducting element via a further transmission line.

9. A reflectometer according to any preceding claim, wherein at least some parts of the system which carry no signals or low frequency signals are covered by an RF absorbing material, the low frequency signal being signals in the system other than the said pulse produced by the first photoconductive element and received by the second photoconductive element.

10. A reflectometer according to claim 3, wherein the portion of the transmission lines which extend under the first substrate are thinner than the portions which do not extend under the first substrate.

11. A reflectometer according to claim 3, wherein there is hole in the second substrate to allow illumination of the photoconductive element on the first substrate.

12. A reflectometer according to any preceding claim, further comprising at least one transient voltage diode configured to protect at least one of said photoconductive elements.

13. A reflectometer according to any preceding claims, wherein the first photoconductive element is an generator which receives a pump beam of radiation and the second photoconductive element is a receiver which receives a probe beam of radiation, the pump beam and probe beam being emitted from the same source, the reflectometer further comprising a delay line configured to vary the path length of the pump beam is varied relative to that of the probe beam or vice versa.

14. A reflectometer according to claim 13, wherein the delay line comprises a fast scanning delay section and a slow scanning delay section, wherein said fast scanning delay section is provided by an oscillating rhomboid and said slow scanning delay section comprises a linear delay line.

15. A reflectometer according to any preceding claim, wherein the first photoconductive element is configured as a generator and the second photoconductive element is configured as a receiver, the reflectometer further comprising an AC bias unit to provide an AC bias to said generator and a phase sensitive detection unit configured to perform phase-sensitive detection on the signal measured directly from the receiver device.

16. A reflectometer according to any preceding claim, wherein said second photoconductive element is configured as a receiver, the reflectometer further comprising an amplifier to amplify the output of the receiver and unit configured to provide a input AC impedance of at least 100,000 ohm at the AC bias frequency to said amplifier.

17. A reflectometer according to either of claims 1 or 2, wherein photoconductive elements are coupled to the transmission line arrangement by wire bonds or ribbon bonds.

18. A reflectometer according to any preceding claim, wherein the photoconductive elements comprise GaAs, InP, GaInAs or another III-V alloys.

19. A reflectometer according to claim 3 wherein the electrodes of the photoconductive elements are coupled to the transmission line by a flip-chip bonding methods chosen from, solder ball bumps, conductive epoxy, indium ball bumps or wire ball bumps.

20. A reflectometer system comprising a plurality of reflectometers according to claim 3, wherein a single common first substrate is provided for the plurality of reflectometers such that

the photoconductive elements for a plurality of reflectometers are flip chip bonded at the same time.

21. A reflectometer system according to claim 20, wherein the plurality of reflectometers are arranged in parallel to one another.

22. A method of performing a reflectometry test on a device, the method comprising:
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element using a transmission line; and
providing a termination resistance provided for said transmission line configured to match the impedance of the transmission line.

23. A method of performing a reflectometry test on a device, the method comprising
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;
directing a pulse from the first photoconductive element to a device under test and directing a pulse reflected from the device under test to the second photoconductive element using a transmission line, said transmission line having a three terminal arrangement with the first and second elements provided at separate terminals and an input to the device provided at the third terminal.

24. A method of performing a reflectometry test on a device, the method comprising
providing a source of pulsed radiation;
providing a first photoconductive element configured to output a pulse in response to irradiation from said pulsed source;
providing a second photoconductive element configured to receive a pulse;
directing the pulse from the first photoconductive element to a device under test and directing the pulse reflected from the device under test to the second photoconductive element using a transmission line,

wherein at least one photoconductive element comprises an pair of electrodes provided on the first surface of a first substrate and said transmission line arrangement is provided on a second surface of a second substrate,

the first and second surfaces being provided facing one another such that there is communication of a pulse between the said element and the transmission line arrangement.