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There exists a critical need for efficient local oscillators for heterodyne mixers operating in the 300 to 3000 GHz region. Applications include space-based submillimeter wave imaging arrays, airborne atmosphere spectroscopy, all-weather imaging radar, non-destructive testing, plasma diagnostics, weapon and contraband detection and communications. In order to address these problems, we propose a novel low power semiconductor device which uses time delays from a common optical pulse train to achieve a much higher frequency electrical pulse train, which contains a strong component and appreciable power of the desired submillimeter-wave harmonic for the output and which can be readily coupled electrically or radiatively to a receiver.

In our effort, we developed a concept of linear array of ten optical switches. The microwave output from the switches can be in the 100 - 200 GHz frequency range. In order to implement this concept, a single photo-conductive switch of polycrystalline InGaAs was fabricated and tested.

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FINAL TECHNICAL REPORT

OPTICALLY SWITCHED SUBMILLIMETER-WAVE OSCILLATOR

SUBMITTED BY: M.G. SPENCER AND X. TANG

U. S. ARMY RESEARCH OFFICE

GRANT DAAL-03-92-G-0257

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Introduction

There exists a critical need for efficient local oscillators for heterodyne mixers operating in the 300 to 3000 GHz region. Applications include space-based submillimeter wave imaging arrays, airborne atmosphere spectroscopy, all-weather imaging radar, non-destructive testing, plasma diagnostics, weapon and contraband detection and communications. In order to address these problems, we propose a novel low power semiconductor device which uses time delays from a common optical pulse train to achieve a much higher frequency electrical pulse train, which contains a strong component and appreciable power of the desired submillimeter-wave harmonic for the output and which can be readily coupled electrically or radiatively to a receiver.

In our effort, we developed a concept of linear array of ten optical switches. The microwave output from the switches can be in the 100 - 200 GHz frequency range. In order to implement this concept, a single photo-conductive switch of polycrystalline InGaAs was fabricated and tested.

List of Appendixes

- Patent Application-Optically Switched Submillimeter Detector
- Picosecond Photoresponse in Polycrystalline Indium Gallium Arsenide Grown by Molecular Beam Epitaxy (Submitted Applied Physics Letters)

Problem Statement

Oscillators operating in the submillimeter region must have reasonable power (in the range of milliwatts up to watts) and are required to cover a wide spectral range. Lasers developed for this purpose are individually restricted to essentially one single wave length. Some tunability can be achieved by optical techniques but only over very limited bandwidth. Microwave generators, such as carcinotrons, do not operate efficiently at wavelengths shorter than one millimeter and are excessively heavy, consume considerable power, and have short lifetimes restricting their use in flight missions.

Available solid state oscillators, such as GaAs Gunn diodes, and IMPATT's are highly efficient and tunable but are limited to frequencies up to about 125 GHz. Likewise, recent research on quantum well negative differential resistance oscillators project to only comparable power-frequency performance. Higher frequencies can be achieved by generating harmonics of the solid state oscillator frequencies using solid state nonlinear devices such as GaAs varactors or varistors. This approach is limited by the reduced power output at the higher harmonic frequencies. This latter limitation is being partially overcome by developing device arrays to increase the total power output[1,2]. Ultimately, the device cut-off frequencies will still limit this approach to frequencies not much greater than 1000 GHz.

Important Results

Development of Test Experiments and Refinement of Device Design

During the course of this grant, we refined the ideas about our device and potential ways to realize it. These new ideas resulted in the patent application filed in late 1992 and revised in 1993 (**see Appendix 1**). In the basic device, we propose to use a number of semiconductor switches driven by laser pulses where each of the switches "see" a variable optical path length and delay from the laser. This concept provides a means of transforming optical pulses to electrical pulses at submillimeter wave frequencies. The device combines the use of semiconductor photoconductive switches (Auston type)[2,3], with a pulsed laser to produce very high local oscillator frequencies (greater than 1 THz). The higher frequencies are produced by multiplying the laser repetition rate by a number N, equal to the number of photoconductive switches. This multiplication is accomplished by introducing an optical phase delay between successive switches. This phase delay can be produced by several methods, such as optical fibers of varying lengths or an optical wedge of continuing varying thickness. The Auston switch is a structure formed by a metal gap placed on a high resistivity photoconductor material (semi-insulating GaAs, InP, as well as low temperature GaAs have been used as the high resistivity material). The switches are biased with a voltage source, where the light pulse arriving at a single switch produces electron-hole pairs between the gap and forms a low resistance path in the gap allowing current to flow. Single switches of this type have demonstrated pulse widths of 0.46 ps[3,4].

We completed the design assembly and alignment of an optical system for the demonstration of the device as shown in **Figure 1**. The mode locked laser outputs a beam.

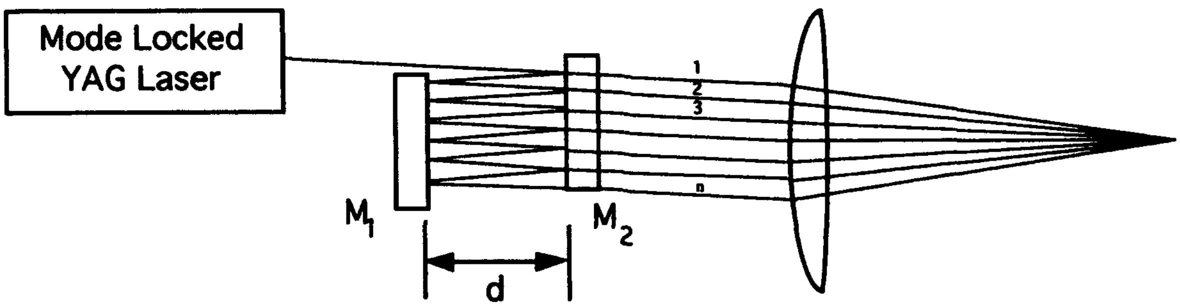

Figure 1

The mode locked YAG Laser outputs the beam with power of ~ 8 W, at 1.06 M wavelength mode locking pulse width of 100 ps at a repetition rate 78 MH. The pulse duration is about 12.8 ns. The peak power for every single pulse is about 10^3 W. We want to divide this power equally into 10 beams by using two mirrors which are coated with step varied reflection coating. The time separation between a pulse and the one next to it equals to the roundtrip time of light between the mirrors.

For first step, we choose M_1, with R_1,=99.8% and M_2 with R_2~95%, so a Peak powers are about 10^3 x 5% ~ 50W for beam 1, 50 x 95% ~ 47.5W for beam 2, 45W for beam 3. Then a lens is used to focus all the beams together on a detector or a fast switch by very fine adjustments of the mirrors and lens. The first three beams can be focused on same point, the area of which is less than $0.0036MM^2$. When we use a detector (Antel AR-S2) to observe the signal, a stable wave form can be shown on sampling oscilloscope similar to **Figure 2**.

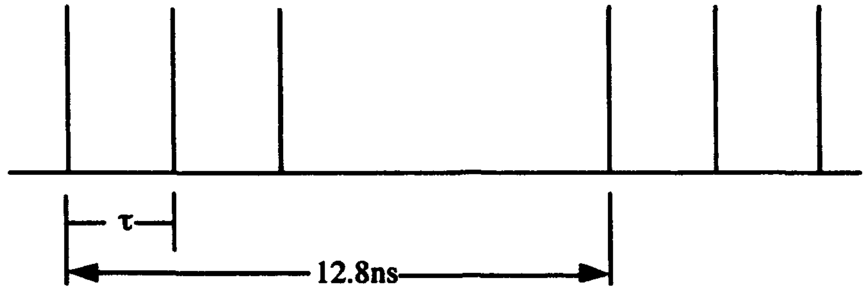

Figure 2

The time separation can be adjusted by adjusting the distance between two mirrors.

Measurement of Picosecond Response in Polycrystalline Indium Gallium Arsenide

In order to be able to use the aforementioned test system, it is necessary to use the highest power laser intensity which means the YAG frequencies. This means that the oscillator must be fabricated from a detector sensitive in this wavelength region. We developed and tested such a detector in conjunction with investigators at Lawrence Livermore National Laboratories (**see Appendix 2**). In this detector, polycrystalline indium gallium arsenide ($In_xGa_{1-x}As$; x=0.4) grown on silicon dioxide (SiO_2) by molecular beam epitaxy (MBE) has been investigated for picosecond photoconductivity. Photoconductive devices with 15-μm gap length between ohmic contacts have been fabricated and tested. A photocurrent transient response of 11 ps full width at half maximum (FWHM) was measured.

List of Publications

- Picosecond Photoresponse in Polycrystalline Indium Gallium Arsenide Grown by Molecular Beam Epitaxy (Submitted Applied Physics Letters)

Participating Personnel

- Dr. M. G. Spencer, Professor Electrical Engineering
- Dr. X. Tang, Graduate Associate Professor
- Craig Scott, Graduate student

REFERENCES

1. W.W. Lam, C.F. Jou, N.C. Lauhmann, Jr., and D.B. Ruthledge, "Diode Grids for Electronic Beam Steering and Frequency Multiplication", Journal of Infarred and Millimeter Waves 7, 27 (1986)

2. R.J. Hwu, C.F. Jou, W.W. Lam, B. Hancock, U. Lieneweg, N.C. Luhmann, Jr., J. Maserjain, and D.B. Ruthledge, "Watt-Level Millimeter-Wave Monolithic Diode-Grid Frequency Multiplier", 1988 IEEE MTT-S International Microwave Symposium, New York, Mary 1988; to be published in Symposium Digest

3. A.C. Warren, J.M. Woodall, J.L. Freeouf, D. Grischowsky, D.T. McInturff, M.R. Melloch and N. Otsuka, "Otsuka, "Arsenic Precipitates and the Semi-insulating properties of GaAs Buffer Layers grown by Low-temperature Molecular Beam Epitaxy", Applied Physics Letters 57 (13) 1331 (1990)

4. Martin Van Ester and Daniel R. Grischkowsky, "Characterization of an Optoelectronic Terahertz Beam System", IEEE Transactions on Microwave Theory and Techniques 38 (11), 1684 (1990)

5. C. Shu, X.-C. Zhang, E.S. Tand and P.H. Auston, "Optoelectronic Generation of Time Division Multiplied Ultrafast Bit Stream on a Coplanar Waveguide", Applied Physics Letter 51 (27) 1990

APPENDIX

APPENDIX 1

JPL Case No. 18547
NASA Case No. NPO-18547-1-CU
Attorney Docket No. JPL/045-92

PATENT APPLICATION

OPTICALLY-SWITCHED SUBMILLIMETER-WAVE OSCILLATOR AND RADIATOR

BACKGROUND OF THE INVENTION

Origin of the Invention:

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected not to retain title.

Technical Field:

The invention is related to submillimeter wave generators and in particular to a submillimeter wave generator which does not depend upon non-linear semiconductor processes to produce power, but rather employs optically-controlled electronic switches connected to a voltage source providing the submillimeter radiation power.

Background Art:

There are no efficient submillimeter wave sources operating in the 300 to 3000 GHz region which are light-weight and produce on the order of a milliwatt power, despite current efforts to find such a source. The need for efficient local oscillators for heterodyne mixers in the 300 to 3000 GHz region is critical because of the potential applications in space-based submillimeter wave imaging radar, non-destructive testing, plasma diagnostics, weapon and contraband detection and communications. Such local oscillators must have reasonable power (in the range of milliwatts up to watts) and are required to cover a wide spectral range. The art has made numerous unsuccessful attempts to meet this need, but so far there appears to be little prospect of succeeding, as will now be described.

Lasers developed for this purpose are (individually) restricted to essentially one single wavelength. Some tunability can be achieved by optical techniques, but only over very limited bandwidth.

Microwave generators capable of generating submillimeter waves, such as carcinotrons, do not operate efficiently at wavelengths shorter than one millimeter and are excessively heavy, consume considerable power and have short lifetimes, making them relatively unsuitable to use in space flight.

Available solid state oscillators, such as GaAs Gunn diodes and IMPATT diodes are highly efficient and tunable but are limited to frequencies up to about 75 and 125 GHz, respectively, because of fundamental limitations on maximum current density in such devices. Recent research on quantum well negative differential resistance devices or oscillators has produced results characterized by very low power (less than microwatts) at much higher frequencies than the solid state oscillators discussed above. Higher frequencies (up to 500 GHz) have been achieved also by generating harmonics of the oscillator frequency using solid state nonlinear devices such as GaAs varactors or varistors. This approach is limited by reduced power output at the higher frequencies, typically less than micro-watts. As disclosed in U.S. Patent No. 4,954,864 by Joseph Maserjian, one of the inventors herein, some attempts have been made to partially overcome this limitation using large arrays of such devices. However, the highest frequencies achieved in such quantum well devices are on the order of only 500 GHz because of fundamental limitations.

Thus, it has not seemed possible to provide a submillimeter wave source operating in the 1000 to 3000 GHz frequency range with power output on the order of milliwatts.

It is therefore an object of the invention to produce submillimeter waves without relying upon nonlinear semiconductor devices such as PN junctions and quantum wells to provide the power, so as to escape the fundamental constraints which so far have held submillimeter power output at 500 GHz to sub-microwatt levels.

It is a further object of the invention to provide on a single semiconductor substrate a submillimeter wave source capable of producing submillimeter waves with at least one milli-watt power at frequencies between 300 GHz and 3000 GHz.

It is another object of the invention to provide a submillimeter wave source meeting the foregoing objectives and further having a tunable submillimeter wave output frequency.

These and other objects and advantages of the invention will become apparent in the following detailed description when taken in conjunction with the accompanying drawings.

SUMMARY OF THE DISCLOSURE

In one embodiment, the invention is a submillimeter wave-generating circuit, including a linear array of plural photoconductive switches, apparatus for biasing the switches across a common voltage source, an output load connected to one end of the array, and apparatus for applying an optical pulse beam of repetition rate f_0 to the plural switches so as to generate electrical pulses from the switches traveling along the linear array toward the output load, wherein the plural switches are spaced apart by a spacing D to provide a corresponding switch-to-switch propagation delay of the electrical pulses, whereby arrival times of the electrical pulses at the output load are spaced apart by an arrival period corresponding to a desired submillimeter wave frequency f which is a function of the switch-to-switch propagation delay. In accordance with one aspect, the invention further includes optical delay apparatus for delaying arrival of the optical pulse at successive ones of the switches with successively increasing optical delay times corresponding to a switch-to-switch optical delay difference, whereby the arrival period corresponding to the submillimeter wave frequency f is a function of both the switch-to-switch propagation delay and the optical delay difference. The invention can include tuning apparatus for varying the optical delay difference so as to change the submillimeter wave frequency f.

In accordance with one implementation, the array of switches includes a number of switches not exceeding N, wherein N is on the order of f/f_0. The optical delay apparatus in one version includes apparatus for disposing the linear array at an angle θ relative to the optical pulse. The arrival period is independent of N and is $1/f = (D/c)(n - \sin\theta)$, wherein c is the speed of light and n is an applicable index of refraction.

Generally, the optical delay apparatus includes a wedge-shaped optical medium, which may be either a vacuum or a refractive medium, between a source of the optical pulse and the array of switches. In one version, the optical delay apparatus includes an array of optical fiber channels of successively increasing optical lengths disposed generally perpendicular to the array of switches, each optical fiber channel facing a respective one of the switches, respective ones of the optical fiber channels having respective lengths corresponding to respective optical delays.

In accordance with one implementation, the apparatus for biasing includes metal conductors overlying a highly resistive photoconductive layer and having gaps therein forming each of the switches, the circuit further including a thin film insulated capacitor plate connected to one of the conductors and overlying another one of the conductors along a major portion of the length of the other conductor, the capacitor plate providing a local charge source for each of the switches. Preferablhy, the output load is a free-space radiating antenna connected across the metal conductors. One end of the capacitor plate and one end of the one conductor lie at one end of the array of switches, the antenna being connected across the one end of the capacitor plate and the one end of the one conductor.

In accordance with another embodiment, the invention is a free-space radiating multi-watt submillimeter wave source, including an integrated circuit substrate, an optically active semiconductor layer overlying the substrate, a linear array of opposing metal finger pairs overlying the optically active layer with thin gaps between opposing fingers of each pair, adjacent ones of the gaps being separated by a uniform spacing D for a gap-to-gap propagation delay corresponding to a submillimeter wave frequency regime, a pair of bias bus conductors connected to respective ones of the opposing metal finger pairs, an antenna connected at a first terminal thereof to one of the bias bus conductors at one end of the linear array, and a thin film capacitor having one capacitor plate overlying a major portion of one of the bias bus conductors and connected to a second terminal of the antenna and a dielectric layer lying between the capacitor plate and the underlying one bias bus conductor. The substrate is illuminated with a pulsed optical beam. This embodiment further includes apparatus for preventing light from interacting with the optically active semiconductor layer in a region between adjacent finger pairs. In one implementation, the apparatus for preventing light from interacting with the optically active semiconductor layer in a region between adjacent finger pairs includes open voids in the optically active semiconductor layer in regions bounded by adjacent ones of the gaps. In another implementation, the apparatus for preventing light from interacting with the optically active semiconductor layer in a region between adjacent finger pairs includes an opaque layer overlying discrete regions of the optically active semiconductor layer between adjacent ones of the gaps.

This embodiment can further include apparatus for imposing respective optical delays on arrival of a pulsed optical beam at successive ones of the gaps, whereby the antenna radiates at a submillimeter wave frequency which is a function of both the gap-to-gap propagation delay and a difference between the optical delays at adjacent gaps. Generally, the apparatus for imposing optical delays includes a wedge-shaped optical medium in an optical path to the gaps. In one implementation, the apparatus for imposing optical delays includes wedge of plural successive optical fibers of successively increasing lengths in alignment with respective ones of the gaps at one end thereof for receiving a pulsed optical beam at an opposite end thereof. In the preferred embodiment, however, the apparatus for imposing optical delays includes apparatus for disposing the array at an off-normal angle relative to an incident pulsed optical beam.

In an alternative embodiment, a submillimeter wave-generating circuit includes a two-dimensional planar array of photoconductive switches including plural linear arrays of the plural photoconductive switches, apparatus for biasing the switches across a common voltage source, an output load connected to one end of each one of the linear arrays, and apparatus for applying an optical pulse beam of repetition rate f_0 to the plural switches so as to generate electrical pulses from the switches traveling along each one of the linear arrays toward the respective output loads, wherein the plural switches within each linear array are spaced apart by a spacing D to provide a corresponding switch-to-switch propagation delay of the electrical pulses, whereby arrival times of the electrical pulses at each one of the output loads are spaced apart by an arrival period corresponding to a desired submillimeter wave frequency f which is a function of the switch-to-switch propagation delay. This alternative embodiment can include optical delay apparatus for delaying arrival of the optical pulse at successive ones of the switches in each linear array with successively increasing optical delay times corresponding to a switch-to-switch optical delay difference, whereby the arrival period corresponding to the submillimeter wave frequency f is a function of both the switch-to-switch propagation delay and the optical delay difference. It can also include tuning apparatus for varying the optical delay difference so as to change the submillimeter wave frequency f.

In one implementation of the latter embodiment, each one of the linear arrays of switches includes a number of switches not exceeding N, wherein N is on the order of f/f_0. Preferably, the optical delay apparatus includes apparatus for disposing the linear array at an angle θ relative to the optical pulse, so that the arrival period is independent of N and is $1/f = (D/c)(n - \sin\theta)$, wherein c is the speed of light and n is an applicable index of refraction.

In accordance with a second alternative embodiment of the invention employing a single switch, a submillimeter wave source, includes a photoconductive switch biased across a voltage source and having an output load coupled thereto, apparatus for generating multiple delayed reflections of a single pulsed optical beam of repetition rate f_0, successive ones of the reflections being spaced in time by successive optical delay differences corresponding to a submillimeter wave frequency f, and apparatus for focusing the multiple delayed reflections of the beam onto the photoconductive switch. In one implementation, the apparatus for generating multiple delayed reflections includes a mirrored cavity having a top reflective surface and a bottom surface facing the top reflective surface, the bottom reflective surface being partially reflective and partially transmissive in a direction toward the apparatus for focusing. The apparatus for generating the reflections generates N reflections of the beam, wherein $N = f/f_0$.

The invention is also embodied in a method of generating submillimeter wave radiation using an integrated circuit having a linear array of photoconductive switches biased across a voltage source with an output load at one end thereof and characterized by a spacing D corresponding to a switch-to-switch propagation delay, the method including illuminating the linear array with a pulsed laser beam of repetition rate f_0, and holding the array at an angle θ relative to a normal to an optical path of the laser beam so as to impose an optical delay difference in arrival of each pulse of the beam at adjacent ones of the switches. The output load receives successive pulses from the switches at a submillimeter wave frequency $f = 1/[(D/c)(n - \sin\theta)]$, wherein c is the speed of light and n is a factor related to an index of refraction. This method further includes a tuning step of rotating the array so as to varying the angle θ to change the frequency of the submillimeter wave radiation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a first simplified embodiment of the invention employing microstrip elements.

FIG. 2 is a side view corresponding to FIG. 1.

FIG. 3 is a top view of a second embodiment of the invention constituting a free space line radiator.

FIG. 4 is a side cut-away cross-sectional view corresponding to Section 4-4 of FIG. 3.

FIG. 5 is a cut-away cross-sectional corresponding

Picosecond photoresponse in polycrystalline indium gallium arsenide grown by molecular beam epitaxy

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Abstract

Polycrystalline indium gallium arsenide ($In_xGa_{1-x}As$; x=0.4) grown on silicon dioxide (SiO_2) by molecular beam epitaxy (MBE) has been investigated for picosecond photoconductivity. Photoconductive devices with 15-µm gap length between ohmic contacts have been fabricated and tested. A photocurrent transient response of 11 ps full width at half maximum (FWHM) was measured by photoconductive sampling techniques. Furthermore, these devices exhibited <1 µA of dark current with a bias voltage approaching 100 V. A responsivity of 45 mA/W at 1.3 µm wavelength was measured for this unoptimized photodetector configuration. An effective mobility is estimated to be ~30-40 cm^2/V-sec.

Picosecond photoconductivity has been well established over the past decade utilizing a variety of materials including silicon[1] and III-V semiconductors[2-4]. The techniques for achieving picosecond photocurrent response times include radiation damage[1,4], deposition of polycrystalline[5] or amorphous[6] semiconductor materials, or the growth of III-V semiconductors by molecular beam epitaxy (MBE) at reduced substrate temperatures[7]. For the majority of the above referenced materials, the optimal efficiency occurs over the visible to near infrared spectral range, thereby limiting them from applications for 1.3-μm optoelectronic integrated circuits and networks. For these longer wavelengths, picosecond photoconductivity has been demonstrated in InGaAs bombarded by Be^+ to reduce the lifetime[4,8,9]. In this case the InGaAs was grown by MBE or organometallic vapor deposition, and was lattice matched to an InP substrate in order to obtain high crystalline quality. A direct tradeoff was exhibited between mobility and lifetime as a funtion of Be^+ implant dose. InGaAs photoconductors having impulse responses of 2 ps full width at half maximum (FWHM) have been demonstrated, with corresponding responsivity of 20 mA/W. The inherent problem with InGaAs photodetectors is the excessive dark leakage current resulting from the narrow bandgap and low Schottky barrier height (0.2 eV) for metals which are commonly used. This results in excessive noise, thereby reducing the effective signal-to-noise ratio for receivers using these photodetectors. For applications below the 10-20 GHz regime, InGaAs/InAlAs and InGaAs/GaAs metal-semiconductor-metal (MSM) photodiodes have been demonstrated on InP[10,11], and GaAs[12] substrates having high responsivities at 1.3 μm wavelength. The speed of these devices is limited by the transit time of the photogenerated carriers, rather than the carrier lifetime. More recently, InAlAs/InGaAs MSM photodiodes on InP substrates have been fabricated with 0.25-μm feature sizes[13]. These devices have demonstrated >30 GHz bandwidth which is limited by the package, and a responsivity of 0.15 A/W at 1.3-μm wavelength. InGaAs grown by MBE at reduced substrate temperatures has also been demonstrated as a viable approach for achieving ultrafast photodetectors with improved responsivity in the 1.3-1.6 μm range[14,15]. Although these results demonstrate photocurrent transient responses in the subpicosecond regime for low temperature grown InGaAs, there remains the critical issues of effective mobility and dark leakage current. Furthermore, the performance of photodetectors fabricated from this material critically depend on growth and annealing conditions.

Photoconductive devices have been fabricated from polycrystalline $In_{0.4}Ga_{0.6}As$ grown on SiO_2 by MBE. The substrates used were 2" silicon, <100>, 20 Ω-cm p-type. A 1-μm layer of SiO_2 was thermally grown. Prior to placing the substrate under vacuum in the MBE, the SiO_2 surface was prepared by cleaning in hot TCL, acetone, and methanol (200° C, 15 minutes each). Approximately 1-μm of $In_{0.4}Ga_{0.6}As$ was grown directly on the SiO_2 at a substrate temperature of 420° C and a nominal growth rate of ~1-μm/hr. The material was doped slightly p-type during growth in an attempt to pin the Fermi-level at mid-gap. As expected, the epitaxial layer was polycrystalline as exhibited by the reflective high energy electron diffraction (RHEED) pattern. Photoconductive devices were fabricated in a standard autocorrelation test circuit configuration[16]. The circuit simply consists of a 100-μm microstrip transmission line with a 15-μm gap representing the photoconductor. Sampling photoconductors are placed at various intervals along the transmission line. The transmission line electrodes are AuGe/Ni/Au (250Å/50Å/3000Å), which were patterned using standard photolithographic and liftoff techniques. The contacts were alloyed at 400°C for 3 minutes.

The dc performance of the polycrystalline $In_{0.4}Ga_{0.6}As$ photoconductors was determined by measuring the current-voltage characteristics in the dark and with incident 1.3-μm optical power. These results are shown in Fig. 1. From this it can be seen that the dark current is <1 μA for bias voltages approaching 100 V. The resistance of this device is $>10^8$ Ω, and the resistivity is estimated to be $\sim 10^5$ Ω-cm. The top curve in the figure is with 5 mW of 1.3 μm optical power incident on the photoconductive device. The corresponding responsivity at a bias of 90 V (1.5 V/μm) is 45 mA/W. To characterize the impulse response of the polycrystalline $In_{0.4}Ga_{0.6}As$ photoconductors, autocorrelation measurements were conducted[14]. The optical excitation is provided by a Nd:YAG mode-locked laser, which is pulse compressed and frequency doubled resulting in a ~7 ps FWHM, 532-nm pulse train at 82 MHz repetition. The autocorrelation response is measured by splitting the beam, which is then focused onto pulsing and sampling photoconductors. The pulsing photoconductor, which has an applied voltage, launches a transient current signal onto the microstrip transmission line which is then sampled by the closure of the sampling photoconductor. The sampled charge is amplified using lock-in techniques, and then displayed by computer. A variable delay between the split optical beams allows for sampling of the entire photocurrent transient. Since the pulsing and sampling photoconductors nominally will have the same transient response, the result is the autocorrelation response. The result of this measurement for the polycrystalline $In_{0.4}Ga_{0.6}As$ photoconductors is shown in Fig 2. The applied bias was 10 V, and the average power incident was 20 mW. Deconvolving (divide by $\sqrt{2}$) to estmate the impulse response for this material gives 11 ps FWHM. Measurement of the electrical signal amplitude with a sampling oscilloscope, and calibration for dispersion effects gives an estimated effective (combined electron and hole) mobility of 30-40 $cm^2/V \cdot sec$.

In conclusion, the high speed photoresponse of polycrystalline $In_{0.4}Ga_{0.6}As$ grown on SiO_2 passivated silicon substrates by MBE has been investigated. The material has exhibited high resistivity (~10^5 Ω-cm) and high speed impulse response (11 ps FWHM). These results demonstrate that with proper scaling of the photodetector device structure, this material has a competitive responsivity-bandwidth figure of merit in comparison with other photodetector technologies for the 1.0-1.3-μm spectral regime. A further advantage is the compatability with virtually any integrated circuit technology since the active detecting layer is grown on SiO_2.

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References

[1]P.R. Smith, D.H. Auston, A.M. Johnson, and W.M. Augustyniak, Appl. Phys. Lett. 38, 47 (1981).

[2]N.G. Paulter, A.j. Gibbs, and D.N. Sinha, IEEE Trans. Elect. Dev. ED-35, 2243 (1988).

[3]A.G. Foyt, F.J. Leonberger, and R.C. Williamson, Appl. Phys. Lett. 40, 447, (1982).

[4]R. Loepfe, A. Schaelin, and H. Melchior, in OSA Proceedings on Picosecond Electronics and Optoelectronics, Vol. 4, T.C.L.G. Sollner and D.M. Bloom, eds. (Optical Society of America, Washington, D.C., 1989), pp. 206-208.

[5]C.Shu, B.B. Hu, X.-C. Zhang, P. Mei,and E.S.Yang, Appl. Phys. Lett. 57, 64 (1990).

[6]D.H. Auston, P. Lavallard, N. Sol, and D. Kaplan,Appl. Phys. Lett. 36, 66 (1980).

[7] F. W. Smith, H. Q. Le, V. Diadiuk, M. A. Hollis, A. R. Calawa, S. Gupta, M. Frankel, D. R. Dykaar, G. Mourou, and T. Y. Hsiang, Appl. Phys. Lett. 54, 890 (1989).

[8]P.M. Downey, J.E. Bowers, C.A. Burrus, F. Mitschke, and L.F. Mollenauer, Appl. Phys. Lett. 49, 430 (1986).

[9]R. Loepfe, A. Schaelin, H. Melchior, M. Blaser, H. Jaeckel and G.L. Bona, Appl. Phys. Lett. 52, 2130 (1988).

[10]O. Wada, H. Nobuhara, H. Hamaguchi, T. Mikawa, A. Tackeuchi, and T. Fujii, Appl. Phys. Lett. 54, 16 (1989).

[11]J.B.D. Soole, H. Schumacher, and R. Bhat, IEDM Tech. Digest, 483 (1988).

[12]D.L. Rogers, J.M. Woodall, G.D. Pettit, and D. McInturff, IEEE Elect Dev. Lett. 9,515 (1988).

[13]M.L. Riaziat, Y.C. Pao, C.Yuen, and R. Marsland, IEDM Tech. Digest, 191 (1991).

[14]S. Gupta, J. Pamulatpati, J. Chwalek, P.K. Bhattacharya, and G. Mourou, in Ultrafast Phenomena VII, C.B. Harris, E.P. Ippen, G.A. Mourou, and A.H. Zewail eds., 297 (1990).

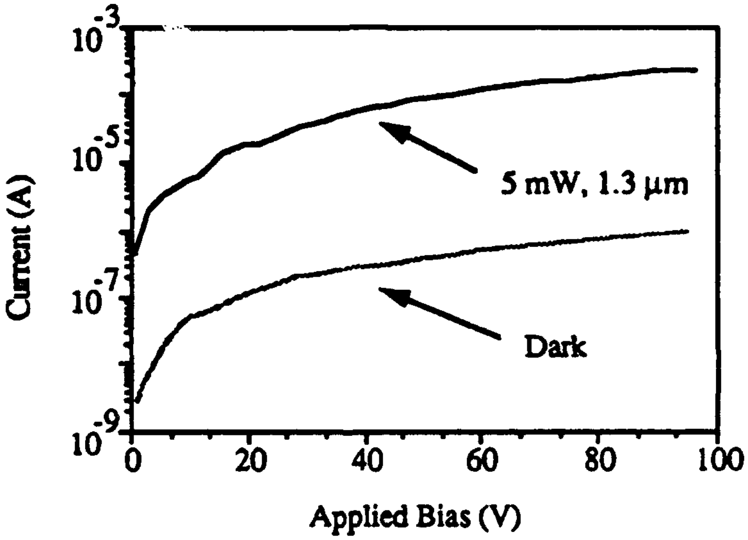
[15]B.C. Tousley, S.M. Mehta, A.I. Lobad, P.J. Rodney, P.M. Fauchet, and P. Cooke, in Ultrafast Electronics and Optoelectronics Technical Digest, 68 (1993).

[16]D.H. Auston, Picosecond Optoelectronic Devices, edited by C.H. Lee (Academic, Orlando, FL, 1984), p. 73.

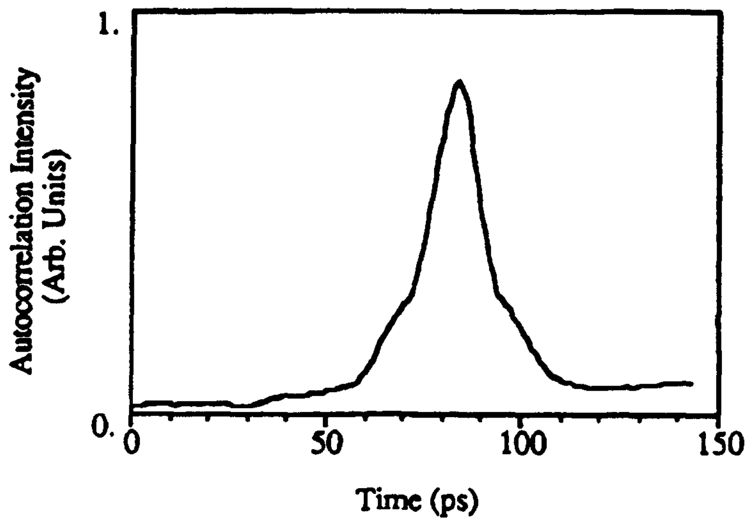
Figure Captions

Fig. 1: Current voltage characteristics of polycrystalline InGaAs photoconductive deveice in the dark, and with 5 mW of 1.3 μm light. The photoconductive gap length is 15 μm.

Fig. 2: Autocorrelation response of InGaAs photoconductive device. The applied voltage was 40 V, and the incident optical pulse was ~7 ps FWHM, 532 nm.



10^{-3}
10^{-5}
10^{-7}
10^{-9}
Current (A)
0
20
40
60
80
100
Applied Bias (V)
5 mW, 1.3 μm
Dark



1.
0.
Autocorrelation Intensity
(Arb. Units)
0
50
100
150
Time (ps)