CONF-901125--4

UCRL-JC--104841

DE91 005433

Received by OSTI
DEC 27 1990

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This paper was prepared for submittal to the
SPIE OPTICON '90,
Boston, MA, 11/4-9/90

October 1990

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Photoconductive switching for high power microwave generation

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ABSTRACT

Photoconductive switching is a technology that is being increasingly applied to generation of high power microwaves. Two primary semiconductors used for these devices are silicon and gallium arsenide. Diamond is a promising future candidate material. This paper discusses the important material parameters and switching modes, critical issues for microwave generation, and future directions for this high power, photoconductive switching technology.

1. INTRODUCTION

Photoconductive switching is a promising technology for High Power Microwave (HPM) generation. We present a discussion of photoconductive switching, describe the critical issues related to microwave generation using this technology, present our knowledge of the current status of this technology, and discuss the critical areas of study in order to develop improved switches for HPM applications.

Photoconductive switches are optically controlled devices.¹ Photons, absorbed in a semi-insulating or high resistivity semiconductor material, create electrical carriers causing the material to change from the highly resistive state into a highly conductive state. In an electronic circuit, if this change in conductivity is sufficiently strong, the device looks like a switch.

Solid state photoconductive switches have many advantages over conventional gas, mechanical, and other solid state switches. These include: high voltage hold-off, very fast switching, negligible trigger jitter, simple mechanical structure, optical isolation of the trigger, high thermal capacity and thermal conductivity, and flexible geometry allowing fabrication of low inductance structures. Switching speed is limited only by the optical trigger speed. Sub-nanosecond switching is routinely achieved.

Since this is a new technology, the power and energy that can be reliably and repeatably switched with photoconductors is much lower than that of several other high power switches. However, photoconductors are uniquely applicable for high power, short pulse and ultra-wideband microwave applications where the fast switching speed is a necessity. At the current state of development, photoconductive switched microwave generators don't directly replace magnetrons, BWO's, and other narrow band HPM devices. The clear challenge for photoconductive switch technology is to increase the power and energy in generated microwave signals without degrading the switching speed and reliability.

Photoconductively switched microwave generators can produce high power, ultra-wideband signals where one is trying to generate only a few cycles per burst. Ultra-wideband is generally defined as a signal having a bandwidth that is at least 25-50% of the center frequency and a power spectrum that is continuous between the minimum and maximum frequency. Generally a frequency of 1 GHz or higher is needed and switching speeds of tens to hundreds of ps are required to precisely generate the signals.

There are several well known circuit configurations that are used with switches to generate microwaves.^{2, 3} The most common are frozen wave and impulse excitation of a microwave cavity. In general, most of these circuits involve some form of microwave cavity and capacitive storage of energy.

2. MATERIAL PROPERTIES

Two semiconductor materials are commonly used for high power photoconductive switches - silicon (Si) and gallium arsenide (GaAs). These materials are the two most common used by the semiconductor industry so considerable effort has gone into improving the crystalline purity and quality of these materials. A third material which is going to be of importance in the future is diamond because of its higher voltage hold-off capability and better thermal properties. Table 1 presents a comparison of the key parameters for photoconductors.

	Silicon	GaAs	Diamond
Band gap (eV)	1.1	1.4	5.5
Resistivity ($\Omega\text{-cm}$)	10^4	10^8	10^{16}
Mobility ($\text{cm}^2/\text{V-sec}$)	1000	5000	1000
Breakdown field (V/cm)	10^5	10^5	10^6
Thermal conductivity ($\text{W/cm-}^\circ\text{C}$)	1.5	0.5	20
Recovery time	100 μs	ns*	ns

* Linear mode - recovery time is much longer in lock-on (μs)

Table 1 Comparison of parameters of interest for the three main semiconductor materials

2.1 Silicon

Silicon is the best known semiconductor material. Single crystals of extremely high purity are available. Silicon has a band gap of approximately 1.1 eV which makes it a strong absorber of the commonly used Nd:YAG laser wavelength of 1.06 μm . Absorption depth of 1.06 μm photons is approximately 1 mm. Being an indirect band gap material Si has a long carrier lifetime (μs -ms). As a result it is useful for generating long electrical pulses using short optical pulses. For example a short (sub-ns) optical trigger pulse can generate carriers in silicon which will continue to conduct current for as long as microseconds to milliseconds. An extremely high gain in energy can be realized with these switches. The energy in the electrical pulse can be several orders of magnitude larger than in the optical pulse used to trigger it because the electrical pulse can be several orders of magnitude longer than the optical pulse. This long pulse capability is generally not useful for microwave generation because of other limitations, such as circuit losses, that prevent the generation of pulses much longer than a few nanoseconds.

One problem with silicon material is due to high leakage current and thermal runaway. High purity silicon can be obtained with a resistivity of several $\text{k}\Omega\text{-cm}$ to several 10's of $\text{k}\Omega\text{-cm}$. Under D.C. bias conditions Si will hold-off only a few kV/cm before leakage current increases sharply due to thermal effects. It has been found, however, that with pulse bias, using approximately 1 μs pulses, electric fields on the order of 40-60 kV/cm can be impressed across a silicon switch without unreasonably high leakage current.

Another way to overcome the thermal runaway problem in Si is to lower the leakage current by using a reverse biased p-n junction. Using a thick lightly doped or intrinsic (i) region between the p and n layers, it is possible to fabricate p-i-n diodes with breakdown voltages well over 1 kV. However, due to effects at the surface related to charge in oxides and dangling bonds at the semiconductor interface it is difficult to maintain a constant surface electric field in such p-i-n diodes. Therefore, surface breakdown usually occurs before bulk breakdown limiting the bias voltage that can be used.

Several techniques have been developed to help control the surface field and help achieve high breakdown voltage. They include beveling the surface to spread out the electric field, the use of "field plates" over the edge of the junction to gain control of that electric field, and the use of field limiting diffusions that extend beyond the edge of the junctions.⁴ These techniques are limited however. The highest breakdown voltage, of which we are aware, achieved in a p-i-n diode was approximately 12 kV.⁵

2.2 Gallium Arsenide

GaAs is the second most common semiconductor material in use today. It has a band gap of approximately 1.4 eV which corresponds to an optical wavelength of approximately 890 nm. However there is a large concentration of defects in even the purest GaAs available today. As a result, there are a large number of deep states within the band gap that can contribute electrons and holes to the conduction process. GaAs can therefore be switched with 1.06 μm light using a process called "extrinsic generation" which uses these deep states. We have measured the absorption depth of 1.06 μm light in typical commercially available GaAs to be approximately 0.5 cm. We would expect this number to vary considerably (perhaps by a factor of 5) for different GaAs samples. Within that uncertainty, it gives us useful information regarding the maximum size of switches that still efficiently use the light.

The larger bandgap of GaAs results in much lower leakage current and correspondingly higher dark resistivity. Semi-insulating GaAs is available with resistivities of $10^7 - 10^9 \Omega\text{-cm}$. In spite of the low leakage current at low electric field, bulk GaAs photoconductive switches like silicon can not be D.C. biased above 4-20 kV/cm. The exact mechanism leading to the premature high leakage current in GaAs is not understood. It is thought to be related to carrier injection and conduction due to trap filling.⁶ With pulse bias, however, electric field levels of 100-140 kV/cm have been achieved. Here the limitation appears to be surface flashover, rather than a bulk conduction effects, because surface treatment and the gas or liquid medium surrounding the chip appears to have the greatest influence on the hold-off voltage. GaAs p-i-n diodes can of course also be made, but very little work has been done to investigate their high voltage properties. Simple bulk GaAs devices, operated under pulsed bias, have been investigated first because of time and funding constraints. Bulk devices are considerably easier to fabricate than p-i-n structures.

GaAs is a direct bandgap material, meaning that carriers can recombine directly across the band gap converting their kinetic energy into an optical photon. This process is much faster than the indirect gap recombination processes in silicon. The carrier lifetime in GaAs can range from a few ps to a few ns. One would expect therefore that GaAs switches could only be used in applications where short (ns) closed times are acceptable. However, an interesting behavior in GaAs leads to switches remaining closed for much longer times than expected. This behavior leads to modes of operation called lock-on and avalanche.

As the bias voltage increases from zero, optically triggered GaAs switches go through the various modes of operation. The first is linear mode. The linear mode is characterized by one electron hole pair produced for each photon absorbed. Therefore the conductivity of the material is, to first order, linearly proportional to the total photon flux illuminating the semiconductor material. Switch conductivity approximately follows the amplitude of the optical pulse. That is, the switch closes as the optical intensity increases, remains closed while illuminated, and opens with a characteristic time constant of the carrier life time once the optical pulse has stopped. Thus the rise time of the electrical pulse is determined by the speed of the laser, and fall time is determined by the material parameter - carrier life time. Generally, switching in the linear mode (resistivity $\leq 0.1 \Omega\text{-cm}$) requires a fairly large optical energy density on the order of $10 \mu\text{J}/\text{cm}^2 - 1 \text{ mJ}/\text{cm}^2$.

Once the bias electric field across the switch exceeds a value of approximately 4-8 kV/cm, a transition occurs to the lock-on mode. In the lock-on mode the laser pulse determines the closing time of the switch, as in the linear mode, but the switch then remains closed or "locked-on" until the current is shut off (by end of line reflection for example).⁷ As the bias electric field is increased further, the optical pulse amplitude can be decreased resulting in an increased gain in energy between the optical trigger pulse and the electrical pulse. The functional dependence between optical trigger energy and bias electric field has not been examined in detail. We do know, however, that at fields in the order of 40-60 kV/cm optical energy densities of the order of a few nJ/cm^2 are sufficient to trigger the device. Further increase in electric field does not seem to increase the trigger sensitivity of the switch. Since this looks like avalanche multiplication we have been calling this latter limit avalanche mode.

As the trigger energy is reduced the switching speed becomes decreasingly dependent on laser speed. The switch eventually exhibits a constant rise time which is related to the physical parameters determining the multiplication phenomenon in the material. This unusual behavior in GaAs is not well understood. It cannot be explained by simple avalanche multiplication, even if a reasonable assumption is made of field enhancement near one electrode. Both lock-on and avalanche modes have a characteristic closed state field of 4-8 kV/cm and are probably two aspects of the same physical

phenomena. Further experimental and theoretical investigation is necessary to understand the mechanisms leading to this behavior.

Without knowing the switching mechanisms it is very hard to predict the maximum switching speed or to determine its limiting factors. We also do not know to what extent filamentary current flow is occurring in avalanche mode. One would expect filamentation because of the classic "s" shaped or current controlled I/V characteristic which theoretically leads to filamentation in switches. If filamentation is occurring, scaling up to higher voltage and current is no longer a simple matter of increasing the length and cross-sectional area as in the linear mode. Filamentation can also lead to localized heating and affect the device life.

In GaAs switches the surface flashover limits the hold-off voltage for a simple slab geometry. It is possible to design a switch structure with a long surface path to overcome this surface flashover problem as shown in Fig. 1. Here the length through the bulk of the switch (L_1) is considerably shorter than the length around the surface of the switch (L_1+L_2). Now to make efficient use of the light, it becomes necessary to coaxially illuminate the switch either through holes in one of the electrodes,⁸ or through a transparent electrode.⁹

Fig. 1 Switch structure to reduce surface flashover

Using this technique it is possible to build switches which have voltage hold-off close to the theoretical maximum of 200 kV/cm for GaAs bulk breakdown. The main drawback of this scheme is that the aspect ratio of the switch must remain "flat," that is, $L_1 \ll L_2$. This results in a large amount of extra GaAs around the active portion of the switch which can interfere with transmission line geometries and make it difficult to achieve ultimate speeds for transmission lines. There is also a limit to how long L_1 can be, dictated by the absorption depth of the light and the speed of light in GaAs.

2.3 Diamond

Diamond is a promising future material for photoconductive switches. Its primary advantages are a higher bulk breakdown field (1 MV/cm) and higher thermal conductivity, ≈ 20 W/cm $\cdot$ °C, compared to silicon (≈ 1.41 W/cm $\cdot$ °C) or GaAs (≈ 0.54 W/cm $\cdot$ °C). The primary drawback of diamond is that its bandgap is considerably larger, approximately 5 eV, and therefore a U.V. laser is required to trigger switching. An optical wavelength shorter than 220 nm is needed. Excimer lasers or quadrupled Nd:YAG can be used to switch diamond. Extrinsic conduction is possible in diamond just as in GaAs, but it would still require a tripled YAG wavelength (337 nm). Furthermore, the manufacture of high purity diamond is in a very primitive state compared to that of silicon and GaAs. It is difficult to get diamond with sufficient crystalline purity and size to be practical for high power switches. Laser technology is the lesser problem.

Once the manufacturing difficulties are overcome however, diamond will assuredly be a strong candidate for high power devices. A factor of 10 increase in breakdown voltage corresponds to a factor of 100 increase in the power and energy in the generated pulse. That, combined with a factor of 15-40 increase in the thermal conductivity, could lead to several orders of magnitude improvement in power output.

3. CRITICAL ISSUES

To establish a basis for examining various materials, circuits, and switching modes it is useful to discuss the issues that are most important in applying photoconductive switch technology to microwave generation.

3.1 Maximum Power and Energy

The number one consideration for HPM generation appears to be the maximum power and energy that can be generated. The exact requirements vary because there are a number of possible applications ranging from microwave weapons to ultra-wideband radar. Generally, higher power, energy, and repetition rate, are better. There are a number of device and circuit parameters that affect the maximum power and energy. They include breakdown voltage and operating mode of the switch, cooling, and laser energy.

Breakdown voltage has a direct impact on generated power because it usually determines the maximum voltage to which a microwave generation circuit can be charged. The power generated is proportional to the square of the voltage (assuming constant load impedance).

The switch operating mode establishes a trade-off between the energy generated by a given laser pulse and the switching speed or frequency of the pulse. In the linear mode of operation, the switching speed is determined by the optical pulse and can be very fast, almost independent of the voltage at which the switch is operated. However the maximum energy generated is limited by the energy in the laser pulse. In lock-on and avalanche modes of operation considerable gain is possible between energy in the laser pulse and energy delivered to load. However, as gain increases the switching time becomes increasingly independent of the laser pulse. It reaches a limit that is strictly a function of the material parameters.

For high power or high repetition rate applications thermal effects due to power dissipation in the switch can become a limiting factor. Repetitive operation is desirable up to several kHz-frequencies for some applications. This places an additional burden on the cooling system. Now both high instantaneous power and high average power are required. Recent developments in microchannel cooling¹⁰ have greatly increased the heat removed from a semiconductor device, but ultimately power dissipation will set an upper limit on the maximum energy and power generated. Considerable further work needs to be done to develop cooling technology for high voltage devices. For good thermal conductivity, the cooling structure must be in intimate contact with the switch. It is conceivable, therefore, that the high voltage might have to be applied across the cooling structure as well as the switch. This high voltage can greatly complicate the cooling structure.

3.1.1 Device life

Device life and failure mechanisms are most important for applications that require a large repetition rate. At several kHz rates, an hour of continuous operation corresponds to several million shots or switch closures.

In GaAs we have observed device life from as little as 10 shots at fields nearing 100 kV/cm to essentially unlimited life at fields below 20 kV/cm. There is also a great deal of variation from device to device. For example, even at 100 kV/cm, some switches have lasted for many thousands of shots.

The mechanism of switch failure is not clear. There has been obvious surface damage on some failed devices while there is no obvious damage of any kind on other devices. This damage (or lack of damage) is true at both medium and high field operation. The current densities in our devices have been $< 5 \text{ kA/cm}^2$ in the majority of devices investigated in linear and lock on operation (with the light penetrating entirely through the switch). In some cases, obvious surface damage is visible after a few thousand shots at current densities of $< 2 \text{ kA/cm}^2$ and repetition rates of $\approx 1 \text{ Hz}$. In addition, in lock-on and avalanche the residual field across the closed switch dissipates power and can limit device life.

3.2 Conversion Efficiency of Prime Power to Microwaves

Conversion efficiency is extremely important because it affects the size and weight which are critical system considerations in almost all applications. Figure 2 shows a block diagram of a typical system for HPM generation using photoconductors. The overall efficiency by which prime power can be converted into radiated microwaves is a complex function of many factors and needs to be analyzed carefully for each specific generation scheme. While a detailed analysis is not appropriate for this discussion, we can discuss some of the most important factors.

Fig. 2 Block diagram of microwave generation system

The prime power is likely to contribute most to volume and weight. The prime power, energy storage, and pulse forming blocks (η_1, η_2) should, however, be very efficient, in the order of 90%, as these are well established technologies. The primary losses are likely to be in the switching (η_3), radiation (η_5), and laser (η_4) blocks. Switching efficiency depends on a variety of factors including the circuit impedance, losses in the semiconductor, and switching speed. It is generally thought that switching efficiencies close to 100% will be achieved. Efficiency of radiation is still an open issue. Antennas are not normally designed for radiation of short pulse wideband signals. New antenna structures need to be developed.

Normally there is a gain, even in the linear mode, in the energy or power ratio between the optical trigger energy and the electrical energy switched. If this gain is sufficient, laser losses become insignificant compared to the other losses. Currently Nd:YAG lasers have efficiencies of less than 1%. Therefore gains of over 1000 are needed. Such high gains are presently only possible in avalanche mode. In fact, it is possible to make very efficient microwave generators using avalanche switches and laser diodes. Unfortunately, avalanche mode is not well understood, and it is not now clear if this mode can be scaled up to the high powers needed. However, there are a number of technologies, such as diode pumped YAG, that have the potential of increasing the laser efficiencies to 1-10%. If for example a future laser has a 10% efficiency, and if a gain of 100 is achieved in the switch (a reasonable number for linear mode), then the amount of prime power needed to trigger the switches would be less than 10% of the total prime power needs. Significant improvements are needed to develop highly efficient, short pulse, high power lasers. However these lasers are useful for a large number of other applications and are likely to be available in the next 5-10 years.

3.3 Maximum Frequency and Agility

The maximum frequency achieved and frequency agility are determined by the generator circuit, switching speed, and optical pulse modulation capabilities, which are either controlled by the laser or external to the laser. Since most of the microwave generation circuits involve the discharge of electrical energy stored in one or more charge lines or cavities, the switching time must be short compared to the period of one cycle. If the switch is too slow the energy will simply be dissipated in the switch and not delivered to the load. As the frequency increases the lengths of charge lines and physical

generate the same total energy. Thus, while photoconductive switches are fast and have low jitter, there is a distinct advantage to keeping the frequency low. We expect photoconductive switches to be most useful in the 1-10 GHz regime.

Frequency agility is a concept usually defined for narrow band signals. It is not clear what frequency agility means, and how to use it in a wideband application. Perhaps more useful than frequency agility would be waveform agility, where the waveform amplitude and period would be controlled to have a uniquely shaped power spectrum. This would require a linear device with fast recovery time and precise shaping of the optical pulse. Linear switches with very short recovery times can be fabricated by creating a large number of defects in the crystal lattice. Unfortunately these short lifetime materials usually also require considerably greater laser energy (as much as an order of magnitude) to switch. Thus there is a trade-off between waveform control and efficiency which must be carefully considered.

4. CURRENT STATUS OF WORK

Photoconductive switching is being studied in several institutions, commercial as well as government and university, in this nation. However, we are only aware of a few groups using them for microwave generation. Currently we are aware of 7 teams of researchers who have active programs in microwave generation and have demonstrated results. These are:

- (1) U. S. Army ETDL / Harry Diamond Laboratory / Rutgers University,
- (2) University of Maryland,
- (3) Lawrence Livermore National Laboratory / Rockwell International / University of Texas at Arlington,
- (4) University of Texas at Arlington,
- (5) Sandia National Laboratory at Albuquerque,
- (6) Power Spectra Inc. / Boeing Aerospace & Electronics, and
- (7) Energy Compression Research Corp.

We have surveyed these teams to compile a picture of the current state-of-the-art. Most teams are using GaAs. However, some experiments are being conducted with Si and Diamond. As mentioned earlier, photoconductors are best suited for generation of very wide band microwave pulses. Most of the microwave pulses generated consist of 1-10 cycles having peak powers of a few MW to several ten's of MW. Switch rise times range from 32 ps to 600 ps. Pulse repetition rates approaching MHz frequencies have been demonstrated for short bursts, but are generally less than 10 Hz. Availability of lasers in the linear mode and switch device life in the lock-on and avalanche modes appear to be the key limiting factors to higher peak power operation. Higher average power will require, in addition, study of device cooling.

5. FUTURE DIRECTIONS

As can be seen photoconductors are useful switches for HPM generation, but considerable additional effort is needed to fully develop this new technology area. An important task is using existing switches to develop HPM systems for demonstration of the technology. In addition further research needs to be done on reliability, failure analysis, physics of switching in GaAs, surface flashover and voltage hold-off, cooling, and development of alternate materials such as diamond. Private companies are best suited to development of products and systems using technology, while the more fundamental research is usually done most cost effectively in universities or national laboratories. We feel that the most effective research teams would be partnerships of government, university, and industrial researchers sharing expertise and effort toward well defined common goals. The goals should have both short term and long term aspects to demonstrate usefulness of current technology, but be considering future growth.

5. ACKNOWLEDGMENTS

The authors wish to acknowledge a number of individuals who have contributed ideas and data for this paper: Dr. William C. Nunnally of the University of Texas at Arlington, Dr. P. T. Ho, Dr. Julius Goldhar, and Dr. Chi H. Lee of the University of Maryland, Mr. Gerald Aschoff, Mr. James O'Bannon, and Mr. Jeremy Stein of Rockwell International, Dr.

University of Maryland, Mr. Gerald Aschoff, Mr. James O'Bannon, and Mr. Jeremy Stein of Rockwell International, Dr. Murray Weiner of U. S. Army Electronics Technology and Devices Laboratory, Dr. Iain McIntyre, and Dr. Oved Zucker of Energy Compression Research Corp. Within Lawrence Livermore National Laboratory we would like to acknowledge our co-workers: R. L. Druce, K. L. Griffin, W. T. White III, M. J. Wilson, and C. G. Dease. In-house work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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