Response of GaAs Photovoltaic Converters Under Pulsed Laser Illumination

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Abstract: - GaAs photovoltaic converters are useful for the conversion of monochromatic light into electrical power in numerous military and industrial applications. In these applications, high output voltages are often demanded. One approach can be used to match the required voltage requirements is single GaAs photovoltaic converter plus DC-DC converter. However, DC-DC converter runs on pulsed electrical energy naturally. Pulsed operation of photovoltaic converter has significant differences from operation under continuous illumination. Many issues must be addressed before high efficiency transmission of power by pulsed laser can be achieved in practical applications. In an effort to understand these issues, a series of studies are undertaken in this paper. The response of GaAs photovoltaic converter to monochromatic pulsed illumination at high intensity is modeled theoretically. As the simulation results showed, the conversion efficiency of GaAs photovoltaic converter to pulsed laser light is dependent on the converter minority carrier lifetime, the width and frequency of the pulses, and the incident power. In addition, three main circuit effects which decrease the efficiency of GaAs photovoltaic converter for pulsed illumination are discussed detailedly. Finally, some feasible approaches are proposed to solve these issues.

Key-Words: - GaAs photovoltaic converter, pulsed laser, minority carrier lifetime, circuit effects, DC-DC converter.

1 Introduction

GaAs photovoltaic (PV) converter illuminated with a monochromatic light source has revealed the highest ever reported photon-energy conversion efficiency (more than 50%) [1-3]. Electrical energy delivery in power-by-light systems represents a promising alternative for copper wires [4]. PV converter transforms optical power into electrical power, which is inherently immune to EMI (Electromagnetic Interference), RF (Radio Frequency), lightning effects, and high voltage [5]. Thus, this technology is also readily available for safe and arm applications since it is immune to magnetic fields, electrical noise and conduction of unexpected electrical currents [6]. Another significant advantage is that the output voltage of PV converters is determined by their materials, and it is almost constant even if the optical input power varies a little. The voltage fluctuation of optical powering is much less than that of electrical powering [7].

For GaAs PV converter applications in military and industry, high output voltages are often demanded. In general, there are essentially two ways of achieving the required voltage. One is that hundreds or thousands of GaAs converters are connected in series to match the required voltage requirements. One of the principal advantages to pursuing this technology is that electric power can be generated in a far smaller volume, and has the possibility of integrating the GaAs PV converter with electronic circuits [8]. However, this method contains a serious defect. The GaAs PV arrays often failed during test or just on exposure to high intensity laser light. Fig.1 shows the failure signature of pathways breakdown. The failure mechanism is dielectric breakdown between the metal lines and the top layer of converters. This explains the failures of most GaAs PV arrays at 600V or greater.

The other is single GaAs PV converter plus DC-DC converter, which boosts the output voltage, with a typical efficiency of 80% [9]. This option has the advantage of simple manufacture, as well as their output voltage being able to be changed by means of the DC-DC converter circuit. However, DC-DC converter runs on pulsed electrical energy naturally. Pulsed operation of photovoltaic converters at high average power has significant differences from operation under continuous illumination. Many technical issues must be addressed before high efficiency transmission of power by pulsed laser can be achieved in practical applications.

The laser considered for power beaming has characteristic pulse width on the order of microsecond at repetition frequencies of hundred kilohertz. In an effort to understand the issues involved in using PV converters to convert power transmitted by the pulsed laser, a series of studies are undertaken in this paper. Modeling of the response of GaAs PV converter to such pulse operation is accomplished and analyzed theoretically. Some circuit effects which decrease the GaAs PV converter efficiency severely are also discussed detailedly, and some feasible solutions are proposed.

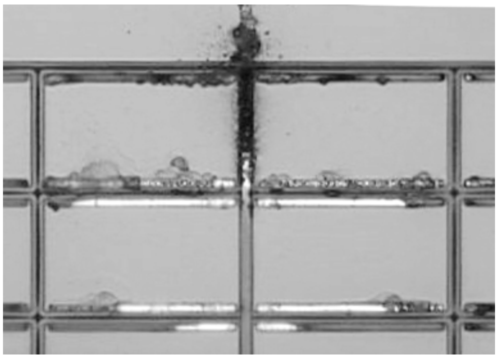

Fig.1 GaAs PV arrays failure signature

2 Modeling Response

2.1 Theoretical Model

Use of a computer model allows us to observe the output of PV converter separated from the circuit interactions. The converter output can then be used as input to the circuit model to understand the array interaction with pulsed incident light. The PC-1D computer code, a finite-element simulation of carrier transport in semiconductor devices [10], is used to model a GaAs PV converter and analyze the converter current during and after the pulse for various conditions. The scheme of the simulated structure of GaAs PV converter is shown in Fig.2, which consists of n-GaAs substrate (doping $5x10^{18}$ cm^{-3}), n-GaAs buffer (doping $5x10^{18}$ cm^{-3}), n-AlGaAs BSF (Back Surface Field) (doping $5x10^{18}$ cm^{-3}), n-GaAs base (doping $5x10^{17}$ cm^{-3}, lifetime 10 ns, diffusion length 3 μm), p-GaAs emitter (doping $2x10^{18}$ cm^{-3}, lifetime 1 ns, diffusion length 1.5 μm), p-GaInP window (doping $5x10^{18}$ cm^{-3}) and p^{++}-GaAs cap layer (doping $5x10^{19}$ cm^{-3}). A modeled double antireflection coating optimized for minimum reflection provides a reflectance of 0%. In addition, the simulation assumes that the front and back surface recombination velocities are $1x10^{4}$ cm/sec.

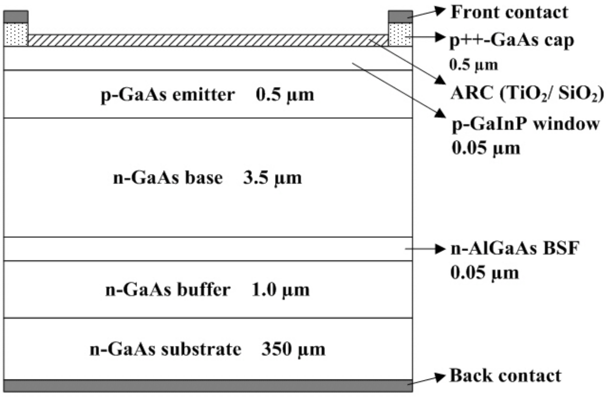

Fig.2 Structure of GaAs PV converter model

Most of the results have been calculated for a peak intensity of 50 W/cm^{2}, which corresponds to nearly 1000 suns concentration. For simplicity, a rectangular illumination pulse is chosen for the model, compared to the slightly rounded pulse of the actual laser. The laser pulse was assumed to be of 25 ns width. From the response to a rectangular pulse, the response to an arbitrary pulse shape can be found.

The characteristic response time of a PV converter to pulsed excitation is related to the minority carrier lifetime of the converter material [11]. Near the maximum power point of a PV converter, the output from the converter is expected to stretch the input pulse by an amount comparable to the minority carrier lifetime of the semiconductor (more properly, by a weighted average of the emitter and base minority carrier lifetimes). The response to pulsed illumination will depend on whether the spacing between pulses is significantly greater than, or significantly less than the minority carrier lifetime in the semiconductor. Typical minority carrier lifetimes for GaAs solar cells are in the range of 10 to 100 ns for undamaged material. If the time between pulses is less than the minority carrier lifetime, the converter responds to the laser effectively as continuous wave operation. If the pulse separation is greater than minority carrier lifetime, the converter responds to each individual pulse at a concentration equal to the peak of the pulse.

2.2 Modeling Results and Analysis

Fig.3 shows the GaAs PV converter short circuit current during and after the laser pulse. The current output was observed to be linear with laser intensity from 0.5 W/cm^2 to 50 W/cm^2. The wavelength is 808 nm. The result is shown for three values of peak intensity. At these levels the output does not significantly depend on intensity. The decay of the current can clearly be seen that there are two distinct components after the pulse. There is an initial rapid drop in current immediately at the end of the light pulse, which is abrupt on the 1 ns time scale. This drop comes from current generated in the emitter and space charge region of the converter. Following the immediate drop is a slow decay, with a time constant equal to half the minority carrier lifetime. This decay is exponential, as is shown by the straightness of the plot on the semi-logarithmic scale. Input laser power with peak intensity of 50 W/cm^2 is used for following simulations.

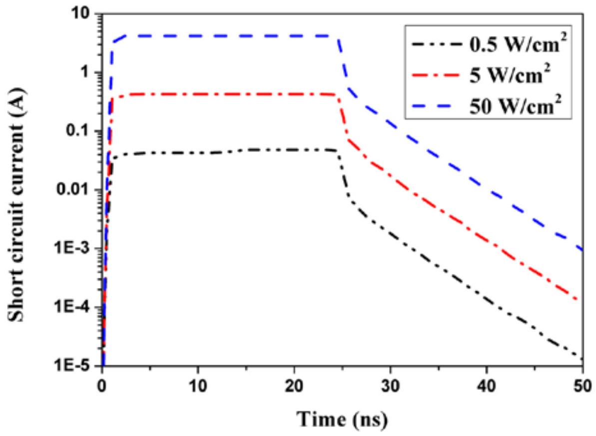

Fig.3 Short circuit current of GaAs PV converter during and after the laser pulse (semi-logarithmic scale)

Fig.4 shows the effects of the incident wavelength. As with the GaAs PV converter, the light absorbed weakly has a slow initial decay and the strongly absorbed light a fast initial rate of decay. The response drops by a factor over a time scale on the order of 25 ns. The 808 nm wavelength corresponds to the available semiconductor laser diode and also proposed operating wavelength in many projects, 840 nm is near the GaAs efficiency peak. The amount of decrease in current at the end of the pulse depends significantly on the absorption depth of the light, and hence, on the wavelength. Thus, initial decay is greatest for the light with the strongest absorption at 808 nm, and is least for the weakly absorbed light at 840 nm. However, that the amount by which the output pulse can be stretched is at most equal to the minority carrier lifetime in the converter base. This is small enough that the difference will not alter the main conclusions of the simulation. The slope of the decay after the initial drop depends on the minority carrier lifetime and is independent of the wavelength.

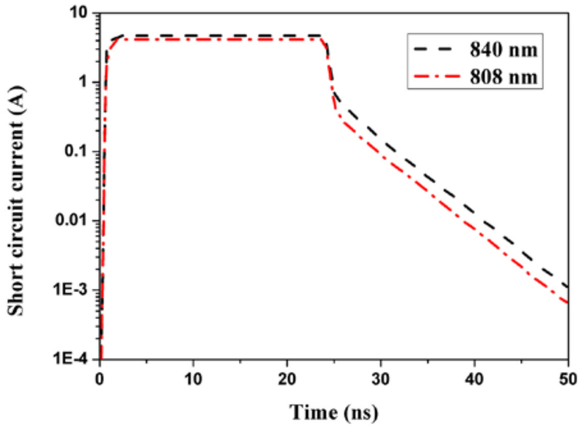

Fig.4 Response of GaAs PV converter to different wavelengths (semi-logarithmic scale)

To examine the initial fast drop in current in more detail, a step-function decrease from steady-state illumination of 50 W/cm^2 to zero was examined in 50 ps time steps. Fig.5 shows this decay for GaAs PV converter biased at short circuit. Since the time constant of this decay not only dependents on the minority carrier lifetime, but also varies significantly on the minority carrier mobility, this decay is apparently driven by the transit time rather than recombination.

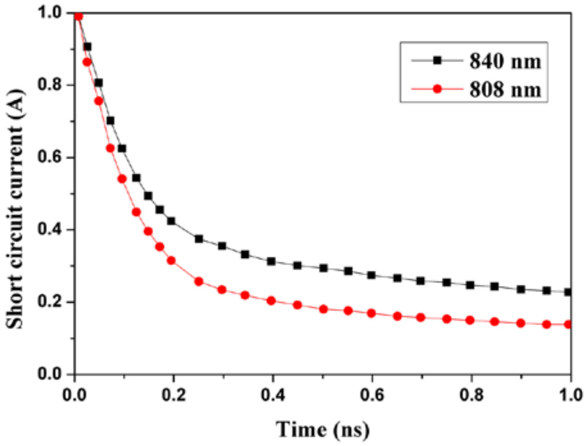

Fig.5 Initial fast drop in short circuit current of GaAs PV converter (liner scale)

3 Circuit Effects Analysis

3.1 Series Resistance

Illumination of the GaAs PV converter with pulsed laser results in significant decrease in efficiency, compared to the continuous-wave laser. For the pulsed laser we used practically in DC-DC converter, the pulse spacing is much greater than the minority carrier lifetime in GaAs, and hence the PV converter will respond to the individual pulses, the peak power during the pulse is higher than average power. Thus, for GaAs PV converters, the peak output current must be larger than the average current for the converter to respond. This means that series resistance will be a very important factor in the efficiency [12]. The output power of the converter is proportional to the current times voltage, while the losses due to series resistance are proportional to the current squared times resistance, series resistance losses reduce the converter performance severely.

The loss to resistance increases linearly with the peak power, as Equation (1).

$$\frac{P_{R_0}}{P_{out}} = \frac{IR_0}{V} \tag{1}$$

Therefore, for this pulse format laser, the GaAs PV converter must be designed to minimize series resistance.

3.2 L-C Ringing and R-C Time Constant

An LRC circuit is formed by the parasitic resistance and inductance in the leads and capacitors and the junction capacitance of the converter. Where insufficient resistance is present for damping a characteristic “ringing” is present in the voltage and current. For a purely resistive load attached to the converter the power delivered depends on Equation (2).

$$p(t) = \frac{1}{T}\int_0^T v(t) \times i(t)\,dt \tag{2}$$

where v(t) and i(t) are periodic signals with period T.

A PV converter is essentially a large area p-n junction, and thus has a large junction capacitance. This, in conjunction with the necessary inductance of the output wiring, results in LC oscillations. Such oscillations result in operation of the converter at a bias different from the peak power point, and hence reduce the output power.

For the power profile delivered to the user, the RC time constant of the PV converter must be taken into account. The junction capacitance of the converter tends to average the laser pulse. A typical junction capacitance of GaAs PV converter is about 0.l μF/cm^2, and a typical resistance may be in the range of 0.01 to 0.1 Ω cm^2. Thus, the expected RC time constants are on the order of 1 to 10 ns. This is for PV converter alone. The wiring and load will add resistance, distributed capacitance and inductance, thus increasing the pulse width.

3.3 Output Inductance

Voltage developed across the converter during the onset of the laser pulse is due to the electric field generated by charged carrier separation, as Equation (3).

$$V = L\frac{dI}{dt} \tag{3}$$

where L is the parasitic inductance in the converter leads, and dI/dt is the time rate of change of the current waveform.

For short pulses, the inductance of the interconnect wiring will also be a significant factor. Inductance will increase the time required for the current to increase from zero to the maximum power point [13], as Equation (4).

$$\frac{dI}{dt} = \frac{V}{L} \tag{4}$$

High inductance will tend to hold the converter at the open circuit voltage. For a rise time of 10 ns, the maximum allowed inductance will be nano-henries or less per converter.

The converter is held at open circuit voltage for a time as Equation (5).

$$t \approx \frac{LI_{sc}}{V_{oc}} \tag{5}$$

where I_{sc} is the short circuit current, and V_{oc} is the open circuit voltage.

During that time, the converter produces little power.

4 Conclusion

GaAs PV converter has higher efficiency than silicon converter, and can be used for missions where high efficiency is critical. Understanding GaAs PV converter behavior under pulsed laser is important in the selection of laser and the design of converter and its external circuit. As the simulation and calculation results showed, the actual effects of pulsed operation are complicated. The conversion efficiency of GaAs PV converter to pulsed laser light is dependent on the converter minority carrier lifetime, the width and frequency of the pulses, and the incident power. Since the spacing between pulses for the laser we used in DC-DC converter is significantly larger than the minority carrier lifetime of GaAs PV converter, it is expected that the output of the GaAs converter will not significantly stretch the pulse, and the GaAs converter will respond to the peak incident power. Thus, the series resistance, the junction capacitance, the parasitic resistance and inductance reduce the GaAs PV converter efficiency severely.

For these problems, there are also some possible approaches to solution. On the premise of avoiding the failure mentioned above, few GaAs PV converters can be connected in series, which has a lower junction capacitance than a single converter, and thus reduces the LC oscillations. By connecting few sub-converters in series, the open circuit voltage is increased, and hence the current rise time is shorter. In addition to PV converter design, the output wiring must also be designed for low inductance. This requirement leads to short wires, wide and flat conductors, and low magnetic-field design with balanced out and return current paths.

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