SAND2007-5733C

Optically Powered Firing Set Using Miniature Photovoltaic Arrays

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ABSTRACT

A firing set capable of charging a 0.05 μF capacitor to 1.7 kV is constructed using a 2.5 mm diameter Series Connected Photovoltaic Array (SCPA) in lieu of a transformer as the method of high voltage generation. The source of illumination is a fiber coupled 3 W 808 nm laser diode. This paper discusses the performance and PSpice modeling of an SCPA used in a firing set application.

Keywords: photovoltaic array, firing set, optical power transfer, high voltage generation, photocell, isolated power source, optically powered firing set

1. INTRODUCTION

Optically powered firing sets have been a topic of interest over the last fifteen years [1] – [3]. Interest has been driven by the advantages of optical power transfer [4]. Safety is increased because the firing set is powered optically thereby decreasing the probability of unintended electrical signals charging the capacitor. This is especially true if an SCPA is used to directly charge the capacitor. With a transformer present in the firing set an unintended low voltage electrical signal could be stepped up to a voltage high enough for the firing set capacitor to be considered charged. Directly generating high voltage with an SCPA eliminates the need for a transformer and therefore will prevent unintended low voltage signals from charging the firing set capacitor. SCPAs are also much smaller than transformers and their associated control circuitry which leads to a reduction in the firing set volume. In addition, an optically powered firing set is immune to electrical interference such as RF, EMI, and lightning.

The construction and geometry of the SCPA is shown in Section 2. Section 3 covers the characteristic equation and performance parameters of the SCPA while under fiber coupled laser diode illumination. Performance parameters that are discussed include short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and peak output power (P_{max}). The capacitor charging performance of the SCPA in a prototype, transformerless, high voltage, optically powered firing set is described in Section 4. In Section 5 modeling of the SCPA is discussed. Modeling of the SCPA is accomplished by first using MathCAD to extract the unknown parameters in the SCPA characteristic equation and second by inputting the characteristic equation with the fitted values into a PSpice Analog Behavioral Model (ABM). Section 6 summarizes the paper.

2. SCPA CONSTRUCTION

The SCPA used in the firing set consists of 2200 individual photocells that are series connected and arranged within a circular geometry (Fig. 1) to form an array 2.5 mm in diameter. The SCPAs are manufactured by Sandia National Laboratories' Microelectronics Development Lab (MDL) using Silicon-On-Insulator (SOI) technology [5]. The top-Si is 5μm thick and the thickness of the oxide is 3μm. Trench isolation is used to separate the individual photocells and is formed by etching through the entire thickness of the top-Si using a dry reactive ion etching technique. The trench is then filled with SiON and the overburden is removed by Chemical-Mechanical Polishing (CMP). A SiO_2 dielectric is used to passivate the top Si layer. SiO_2 is also used to passivate the metal lines. Deposition of the SiO_2 is accomplished by standard plasma deposition. The P/N junction is formed by standard lithographically defined ion implantation which is followed by thermal activation. Dopants used in the n and n+ regions are P and As respectively. The p+ region dopant is B. Figure 2 is a schematic and an SEM cross section of a single photocell that is within the SCPA. The SCPAs are packaged in a DIP filled with Flourinert. Flourinert is an insulating liquid that is used to mitigate the voltage breakdown effects that occur along the surface of the SCPA.

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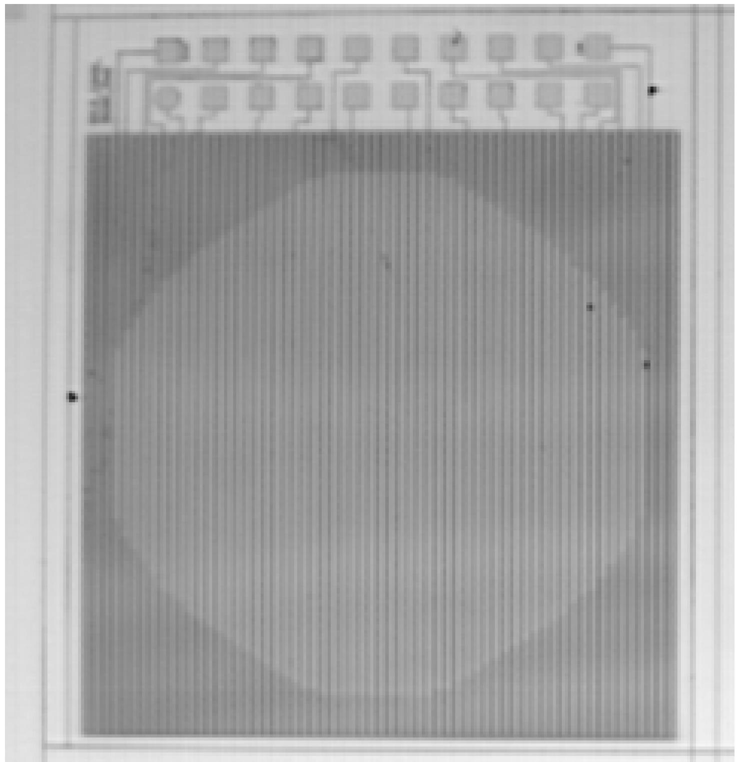

Fig. 1. Photograph of a 2200 cell SCPA. The individual cells are arranged within a circular geometry. This SCPA is capable of generating 1.7 kV.

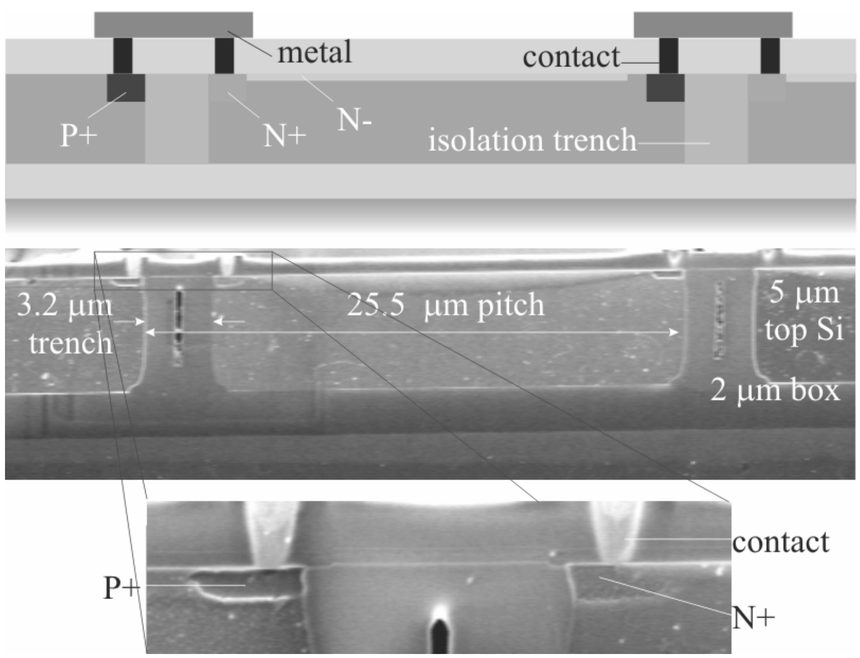

Fig. 2. Schematic (top) and an SEM image (bottom) of a single photocell within the SCPA [5].

3. SCPA PERFORMANCE

An equivalent circuit for a photocell is represented by a diode in parallel with a current source (Fig 3). The current-voltage relationship (I-V curve) of a photocell is described by the following equation,

$$I = I_0 \left[\exp\left(\frac{eV}{nkT} \right) - 1 \right] - I_L , \tag{1}$$

where I_0 is the reverse saturation current, e is the electron charge, n is the diode quality factor, k is Boltzmann's constant, T is the device temperature in degrees Kelvin, and I_L is the illumination generated current.

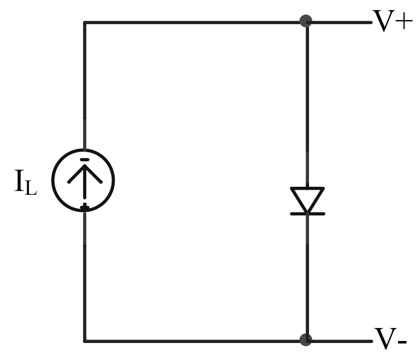

Fig. 3. Equivalent circuit for an ideal photocell.

High voltage is generated by placing photocells in series. When photocells are placed in series the current through the entire array is limited by the photocell that is illuminated the least. This makes the spatial profile of the illumination source a critical parameter [6]. The equation for an SCPA is the same as that of the single photocell with an extra variable, N, in the denominator of the exponential to account for the number of photocells in series and is shown below [2],

$$I = I_0 \left[\exp\left(\frac{eV}{NnkT} \right) - 1 \right] - I_L . \tag{2}$$

Some of the SCPA performance parameters that are of interest when charging a capacitor are I_{SC}, V_{OC}, and P_{max}. The short circuit current is the SCPA current available when driving a shorted load and is equal to I_L. This is the condition at T_0 when charging a capacitor. Open circuit voltage is the maximum voltage generated by the SCPA and this occurs when the load is an open circuit. This is the condition when the capacitor is fully charged. SCPA output power is load dependent and peak output power occurs when the load is such that the bias point is located at the knee of the SCPA I-V curve.

Performance of the SCPA is dependent not only on the device construction but also on the illumination source. An 808 nm fiber coupled laser diode with a 3 W output was used to illuminate the SCPA. The fiber core is 100 um in diameter and has a 0.22 NA. An XYZ translation stage was used to align the fiber to the SCPA. The alignment was optimized by adjusting the translation stage, with the laser diode powered, until a maximum SCPA output was achieved. SCPA data was taken using a Tektronix curve tracer.

The SCPA I-V curve is shown below in Fig. 4. Using 3 W of 808 nm illumination the SCPA is capable of generating an I_{sc} of 94.2 μA a V_{oc} of 1.7 kV, and a P_{max} of 92 mW. The large slope of the I-V curve is caused by an internal parallel resistance within the SCPA and is discussed in more detail in Section 5.

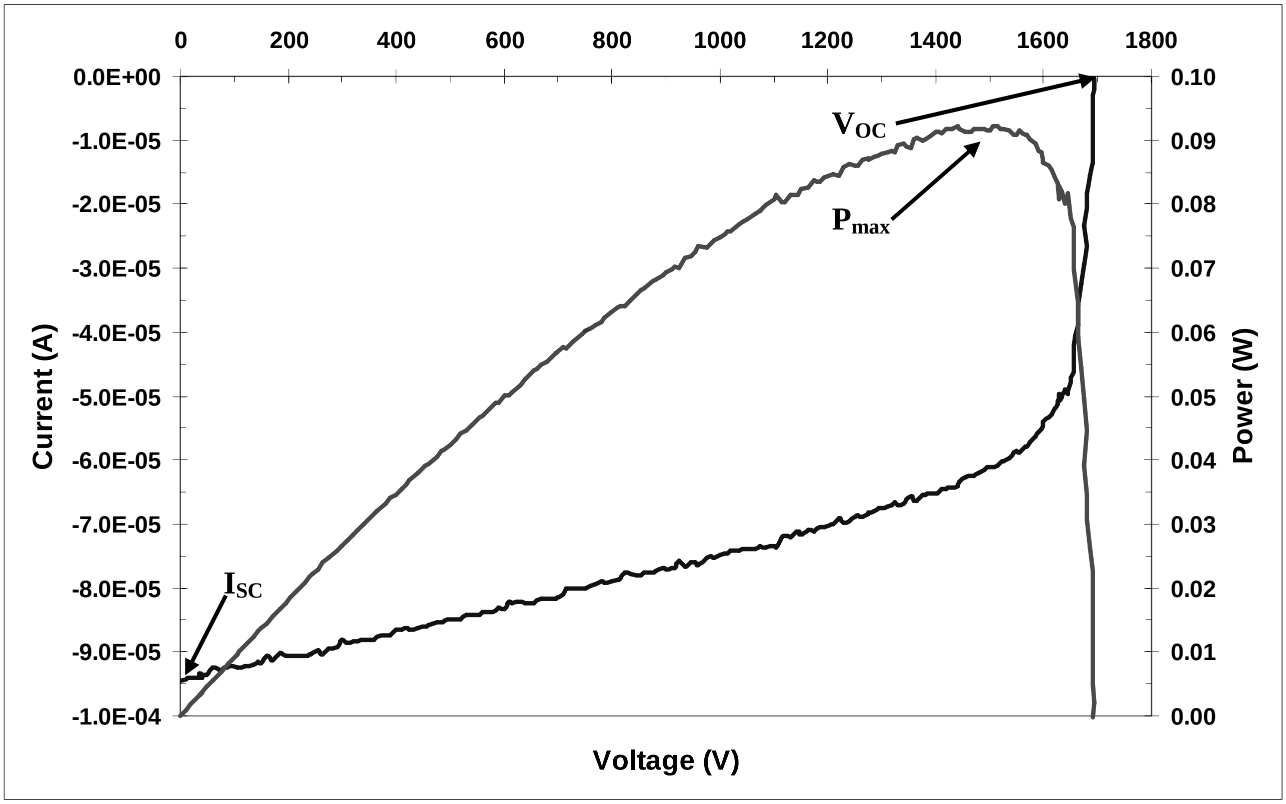

Fig. 4. Plot of the SCPA I-V and power curves.

4. FIRING SET

Basic firing set components consist of a transformer, an energy storage capacitor, a high voltage switch, a load cable, and a load. The method of high voltage generation for this firing set is an SCPA illuminated by a 3 W, 808 nm laser diode. It is this aspect that makes the firing set unique (Fig. 5). This Section discusses the charging of a capacitor with an SCPA.

Equation 3 below describes the charging of a capacitor as a function of time for an ideal SCPA [2],

$$V(t) = \left(\frac{tI_{SC}}{C}\right) - \left(\frac{NnkT}{e}\right)\ln\left(\frac{I_{SC}}{I_{SC} - I_0 \exp\left(\frac{eV}{NnkT}\right)}\right). \quad (3)$$

This equation consists of two terms. The first term on the right is linearly dependent on I_{SC} and capacitance while the second term is logarithmically dependent on I_{SC} and the capacitor charge voltage. Initially the logarithmic term is not significant and the capacitor voltage increases linearly as if it were being charged by a current source. As the capacitor voltage increases the logarithmic term becomes significant and decreases the rate at which the capacitor charges. The charge rate then approaches zero as the capacitor charge voltage asymptotically approaches V_{OC}.

Using the 3 W laser diode and the 2200 cell SCPA it takes approximately 1.5 s to charge a 0.05 µF capacitor to 1.7 kV. Figure 6 shows a plot of the capacitor voltage as a function of time. There are a couple things to note in this plot. First, the rate of charge during the initial 150 ms is low. This is due to the rise time of the laser diode driver which is intentionally slow to prevent overshooting of the current which can damage the laser diode. Second, the charge rate is slightly non-linear throughout the entire charge time and is due to the internal parallel resistance present within the SCPA. The internal parallel resistance must be incorporated into the model in order for the curve fit to converge to a solution. This is covered in the next Section.

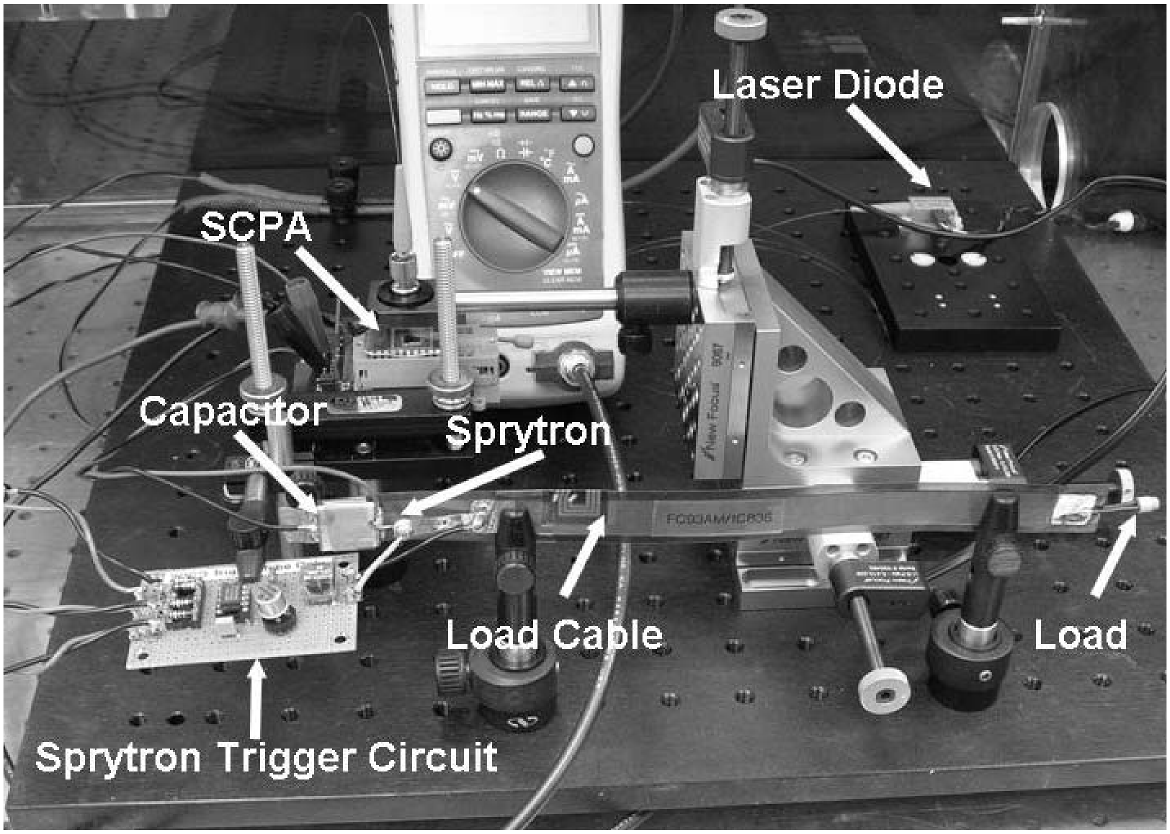

Fig. 5. Photograph of a prototype, transformerless, optically powered firing set.

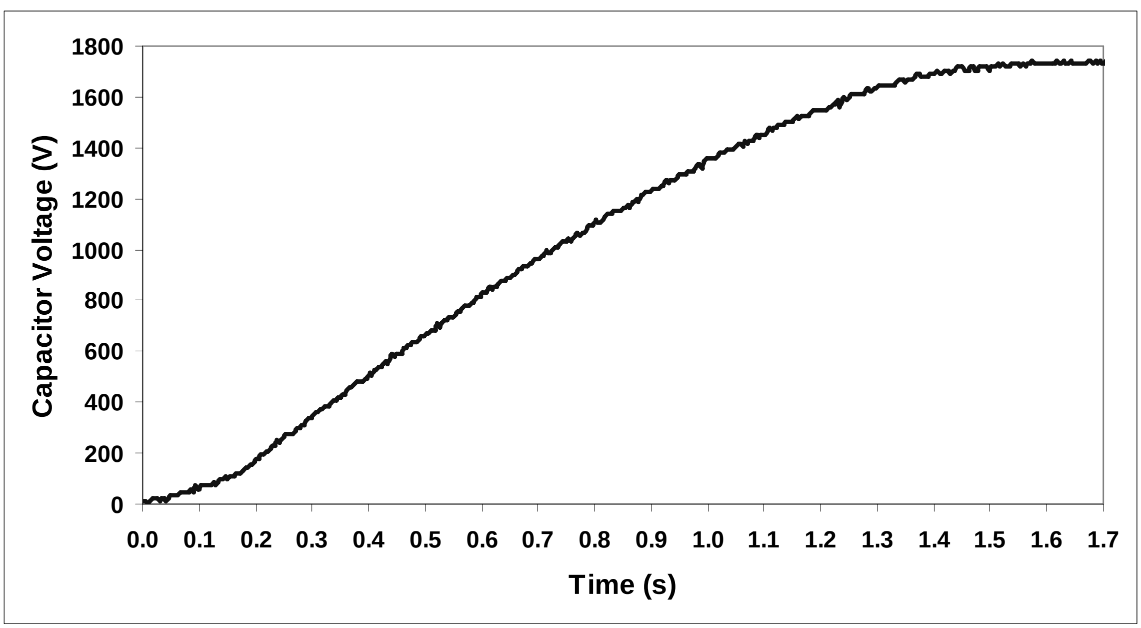

Fig. 6. Plot of the capacitor charge voltage vs. time. Note the effect of the 150 ms rise time of the laser diode.

5. MODELING

Modeling of the SCPA is performed using a two step process. First, a curve fit is performed, using MathCAD, to determine values for the unknown variables in the SCPA characteristic equation. Second, once those values are known an accurate PSpice ABM can be created. These models are useful in a wide variety of circuit simulations including those other than firing set applications.

5.1 Curve Fitting

Before a least-squares curve fit to the SCPA characteristic equation can be made the internal parallel resistance has to be accounted for. The internal parallel resistance acts as a current shunt and reduces the SCPA current that is available to drive a load. Taking into account this internal parallel resistance the SCPA characteristic equation becomes,

$$I = I_0 \left[\exp\left(\frac{eV}{NnkT} \right) - 1 \right] - I_L + \frac{V}{R_P}, \qquad (4)$$

where R_p is the internal parallel resistance. The curve fit gave values of $I_0 = 18.6\text{x}10^{-27}$ A, n = 0.551, and R = $48.3\text{x}10^{6}$ Ω. A plot comparing the test data to the curve fit is shown in Fig. 7.

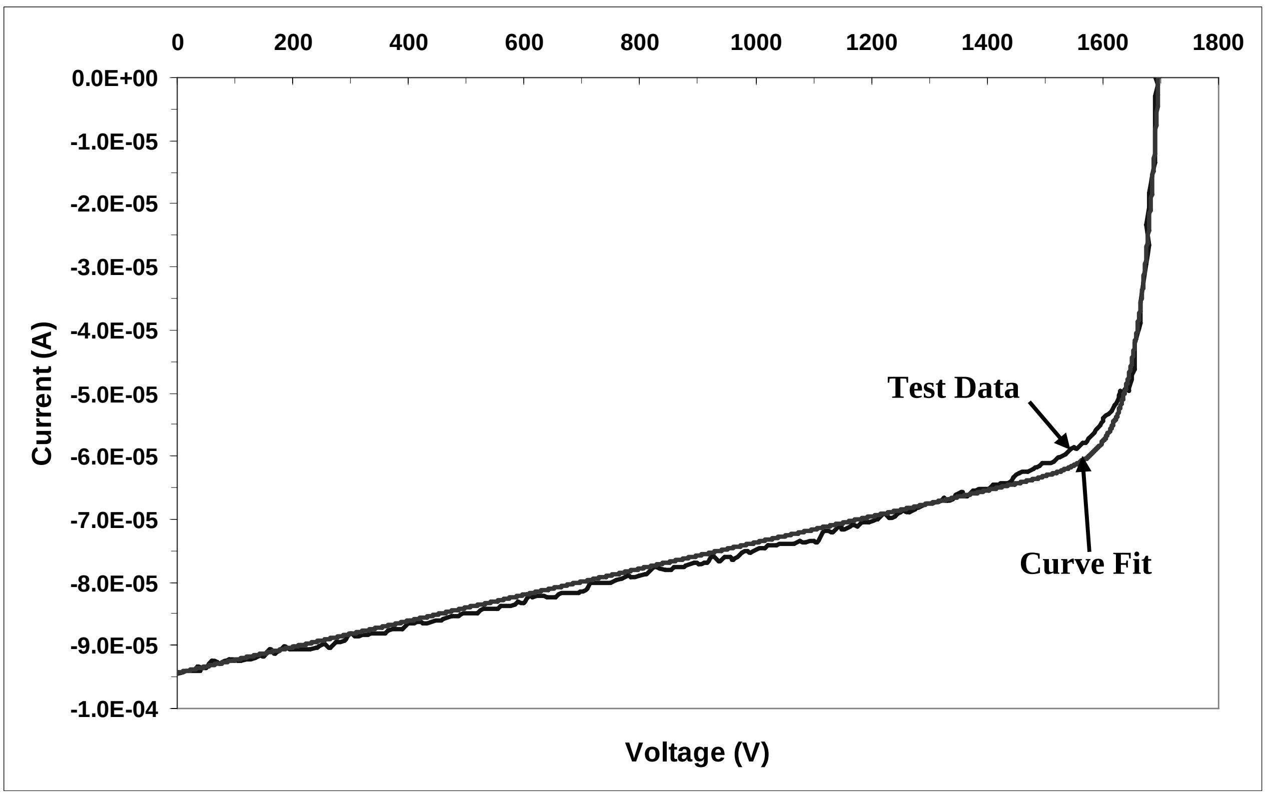

Fig. 7. Plot comparing the test data and the fitted curve.

5.2 PSpice Modeling

SCPA current is non-linearly dependent on the voltage. A PSpice ABM based on a non-linear voltage controlled current source is used to model SCPA performance. The SCPA characteristic equation, with the fitted values, is entered into the ABM. Once the analog behavioral model has been created it is then validated by running a PSpice DC sweep simulation.

A schematic of the charging portion of the firing set including the ABM is shown in Fig. 8. R1 and R2 represent the series resistor pair that is in parallel with the firing set capacitor. This resistance is in addition to the internal SCPA parallel resistance. The series resistor pair serves two purposes. One purpose is that they serve as a voltage divider which provides for a scaled down measurement of the capacitor voltage. The measurement is scaled down by an amount approximately equal to the ratio of the two resistors. The other purpose is to enhance the safety of the firing set. If the parallel resistance was not present within the firing set the capacitor will remain charged unless it is triggered, even if power to the firing set is removed (i.e. turning off the laser diode driver). The parallel resistance allows for the capacitor to bleed its charge without having to trigger the firing set. There are tradeoffs when choosing the value of the resistor pair. If the value is too small the capacitor charge time will increase and the charge voltage will decrease. If the value is too high the capacitor will not bleed down fast enough. PSpice simulation can be used to efficiently determine the appropriate resistance values and resulting charge time and charge voltage.

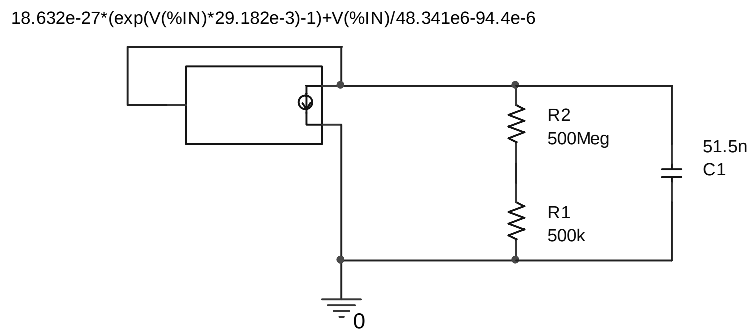

Fig. 8. Schematic of firing set charging circuit. The reduced SCPA equation (Eq. 4) is displayed above the ABM.

PSpice simulation of the firing set charging circuit is in good agreement with the test data and is presented in Fig. 9. The simulated data has been time shifted by 100 ms to compensate for the 150 ms rise time of the laser diode driver.

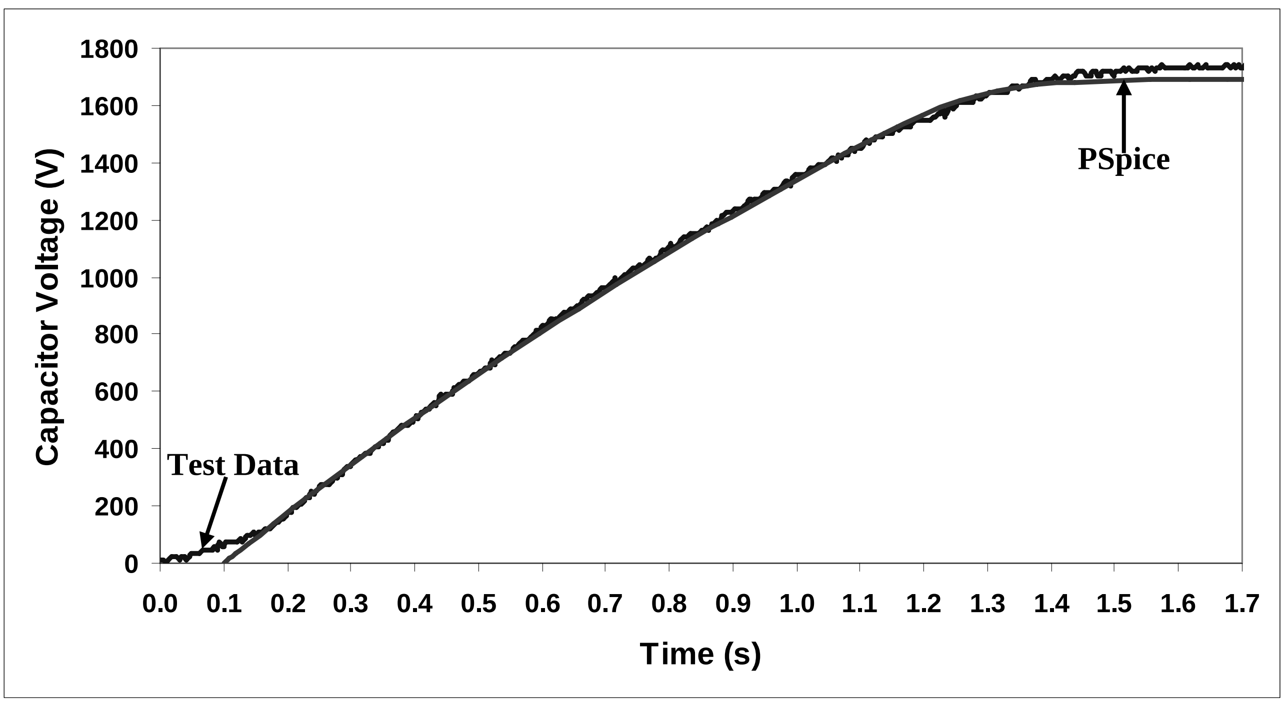

Fig. 9. Plot comparing the PSpice simulation results to the measured data. The PSpice simulation data has been time shifted to compensate for the laser diode driver rise time.

6. SUMMARY

In summary a prototype, transformerless, optically powered firing set has been built. What makes this firing set unique is that an SCPA is used, instead of a transformer, to charge the firing set capacitor. Using an SCPA as the means of high voltage generation leads to increased firing set safety and decreased firing set volume. The increased safety comes from the immunity of optical power transfer to the effects of RF, EMI, and lightning. Decreased volume is achieved by eliminating the transformer from the circuit.

The SCPA used in the firing set consists of 2200 series connected photocells arranged within a circular geometry to form an array 2.5 mm in diameter. Voltage breakdown along the surface of the device has been mitigated with the use of Flourinert. When illuminated with a 3 W 808 nm laser diode the SCPA generates 94 µA of short circuit current, an open circuit voltage of 1.7 kV and a peak output power of 92 mW and is capable of charging a 0.05 µF capacitor to 1.7 kV in 1.5 seconds.

Performance of a firing set charging circuit that uses an SCPA can be modeled by first extrapolating the unknown values in the SCPA characteristic equation using a least-squares curve fit. Second, the characteristic equation, with the extrapolated values, is entered into a non-linear voltage controlled current source ABM. The model generated using MathCAD and PSpice can be used in a wide variety of circuit simulations including those other than firing sets.

Future efforts will involve solving the high voltage breakdown problem along the surface of the SCPA and investigating SCPA performance under high power illumination (>30 W).

REFERENCES

[1] B.H. Rose, "Monolithic, series connected GaAs photovoltaic power converters for optoelectronic component applications," Sandia Report: SAND92-1534, Sandia National Laboratories, Albuquerque, NM September 1992.

[2] B.H. Rose, "GaAs series connected photovoltaic converters for high voltage capacitor charging applications," Sandia Report: SAND97-2306, Sandia National Laboratories, Albuquerque, NM September 1997.

[3] J. Ohsawa, K. Shono, and Y. Hiei, "High-voltage mico solar cell arrays of GaAs with output up to 100 V," 2002 IEEE/LEOS International Conference on Optical MEMS, Lugano, Switzerland, pp.103-4, 2002.

[4] J-G. Werthen, S. Widjaja, T.-C. Wu, and J. Liu, "Power over fiber: a review of replacing copper by fiber in critical applications," in *Optical Technologies for Arming, Safing, Fuzing and Firing*, edited by William J. Thomes, Jr., Fred M. Dickey, Proc. SPIE Vol. 5871, 58710C (2005).

[5] D.J. Stein, R. Nasby, R.K. Patel, A. Hsia, and R. Bennett, "High voltage with Si series photovoltaics," in *Optical Technologies for Arming, Safing, Fuzing, and Firing II*, edited by William J. Thomes, Jr., Fred M. Dickey, Proceedings of SPIE Vol. 6287 (SPIE, Bellingham, WA,2006) 62870D.

[6] J. W. Shelton and F. M. Dickey, "The effects of optical fiber illumination on the performance of series connected photovoltaic arrays for power conversion," in *Optical Technologies for Arming, Safing, Fuzing, and Firing II*, edited by William J. Thomes, Jr., Fred M. Dickey, Proceedings of SPIE Vol. 6287 (SPIE, Bellingham, WA,2006) 6287-14.