1.4 ps rise-time high-voltage photoconductive switching

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We report on the generation of 825 V electrical pulses with 1.4 ps rise time and 4.0 ps duration using a pulse-biased low-temperature-grown GaAs photoconductive switch triggered by an amplified femtosecond dye laser. Dependence of the pulse shape on both electric field and optical energy is observed and discussed.

In recent years many applications have emerged for high-voltage, high-speed switching.[1] The best technique now available for achieving kilovolt electrical pulses with picosecond rise times is laser-driven photoconductive switching. To date, generation of a 1 kV pulse with rise time and pulsewidth of 12 and 70 ps, respectively, has been reported.[2] This was accomplished using a high-resistivity semiconductor with a 1.5 mm switch gap. The fastest rise time that is possible for this switching structure can be determined by calculating the propagation time over a distance equal to the switching gap. For this size gap, a rise time of ~12 ps is found. Using electrodes separated by 10 μm, subpicosecond duration electrical pulses with amplitudes up to 6 V have also been laser generated.[3] The competing needs of having a large photoconductive gap to hold off high voltage and a small gap to maintain high speed have hitherto left kilovolt amplitude and single picosecond pulse generation decoupled.

With the advent of low-temperature molecular beam epitaxy (MBE)-grown GaAs (LT-GaAs), it is now possible to fabricate extremely high-resistivity, high breakdown threshold switches.[4] Now, dc electric fields in excess of 10^5 V/cm are routinely achieved. It is also possible to take advantage of the finite time necessary for thermal runaway or impact ionization to evolve by pulse biasing the switching element for times shorter than breakdown.[1] Using LT-GaAs and the technique of pulse biasing we have applied up to 1.3 kV to a 100 μm gap. Efficient switching of the kilovolt bias requires an optical energy as low as 1 μJ, obtainable with an amplified subpicosecond dye laser. The rise time of the electrical pulse is 1.4 ps. Furthermore, the subpicosecond carrier lifetime of LT-GaAs results in an electrical pulse as short as 4 ps in duration.

A schematic diagram of the experimental configuration is shown in Fig. 1. Our laser (similar to that described in Refs. 4 and 5) generates 150 fs, 2 μJ pulses at 620 nm with a 2 kHz repetition rate, using a two-stage dye amplifier pumped by a frequency-doubled Nd:YAG regenerative amplifier. Part of the frequency-doubled Nd:YAG regenerative amplifier output is used to excite a dc-biased 4-mm-long semi-insulating GaAs switch which is used as the pulse-bias network. The switch is mounted in a microstrip line geometry between a ~10 Ω charge line and a 90 Ω transmission line. Illuminated by an 80 μJ, 80 ps optical pulse at 532 nm, this device produces an electrical pulse which has an amplitude equal to 70% of the dc bias voltage (up to 2 kV) and a duration of 400 ps. This pulse then biases a 90 Ω coplanar stripline (100-μm-wide gold conductors separated by 100 μm) on a LT-GaAs substrate. As the bias pulse propagates along the transmission lines, a 150 fs, submicrojoule optical pulse excites the area between the lines. The high density of carriers formed within the LT-GaAs acts to short the electrodes. This technique of switching, known as "sliding contact," in principle allows total switching of the applied bias voltage.[6] The resulting electrical waveform is shown in Fig. 1. External electro-optic sampling[7] in a LiTaO$_3$ crystal with a 150 fs pulse is used to measure the signal 300 μm from the switch site. In our configuration the crystal has a half-wave voltage of ~4 kV ensuring a response linear with 2% over the range of voltages measured. The calibration error of the measurement is estimated to be ±5% owing mainly to laser intensity fluctuations. Waveforms are recorded for different settings of bias voltage and optical energy.

Figure 2 shows an 825 V pulse with rise time of 1.4 and 4.0 ps duration (full width at half maximum). The negative precursor to the pulse is attributed to the radiation from the dipole formed at the generation site. For incident optical energies greater than 500 nJ we observe saturation of the voltage-switching efficiency, defined as the ratio of

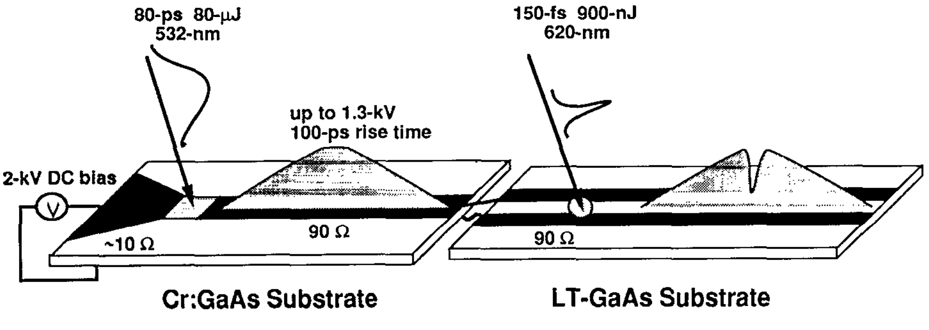

FIG. 1. Schematic of the experimental setup.

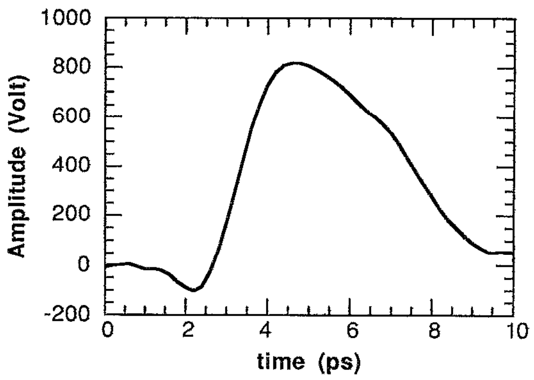

FIG. 2. Waveform showing an 825 V, 1.4 ps rise time, and 4.0 ps duration pulse switched from a 1.3 kV bias with an optical energy of 900 nJ.

switched voltage to applied voltage, as shown in Fig. 3. While the maximum efficiency is ideally 100%, the 70% experimentally measured can be explained by a combination of factors including dispersion and radiation of the propagating electrical pulse as well as contact resistance.

The rise time is ultimately limited by the 100 μm transmission line dimensions; however, we also find a clear dependence on the carrier density. As illustrated in Fig. 4, we observe a degradation from 1.1 to 1.5 ps over the range of optical energy from 100 to 900 nJ. This corresponds to a saturation in the slew rate. The rise time nevertheless appears to be independent of the electric field (Fig. 5). The relation of the rise time to the carrier density is still not well understood. Explanations involving saturation of the current density and strong carrier scattering are presently being investigated.

Although a subpicosecond recombination time was anticipated from previous work,[8] our measurements reveal a much longer recovery time. The tail was also found to increase when either the carrier density or applied electric field was increased (Figs. 4 and 5). Significant local heating due to the extremely high current densities (up to 10^7 A/cm^2) drawn through the switch area may result in generation of additional carriers and explain the long recovery time.

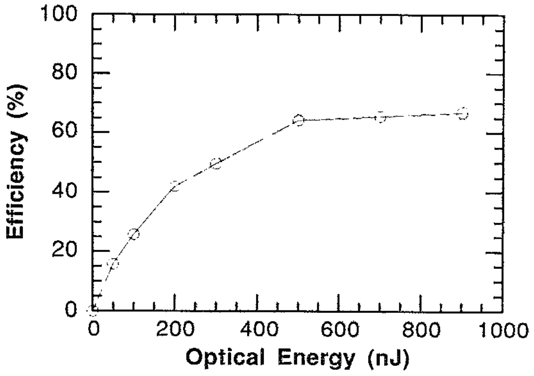

FIG. 3. Switching efficiency as a function of optical energy for an electric field of 100 kV/cm.

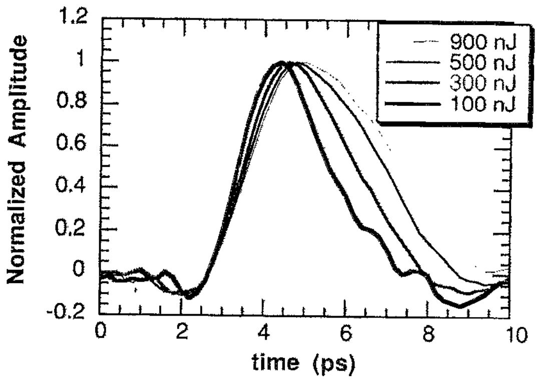

FIG. 4. Pulse shape as a function of optical energy for an electric field of 100 kV/cm.

Another possible explanation for the long recombination time involves intervalley scattering which is known to be strongly dependent on both electric field and carrier density. The switched electric pulse shape reflects the evolution of the current density which is proportional to the product of carrier density and average carrier velocity. In GaAs, a photogenerated hot electron under the influence of a strong electric field can scatter from the central valley to the high-effective-mass satellite *X* and *L* valleys, thereby reducing its velocity and ability to produce current.

The scattering probability increases with the electrical field and, under our experimental conditions, we estimate that more than 80% of the carriers scatter into the satellite valleys within 100 fs.[9] The transfer of those electrons back into the central valley can take several picoseconds.[10] As the pump energy increases so does the carrier density in the central valley. Consequently, the probability for an electron to scatter back into the central valley decreases. As the carriers in the central valley begin to recombine (within a few hundred femtoseconds for LT-GaAs), the probability of carrier transfer from the satellite valleys back to the central valley increases. The satellite valleys can then be seen as sources reinjecting hot electrons into the central valley at a rate dependent on the relative carrier populations which are function of optical fluence, electric

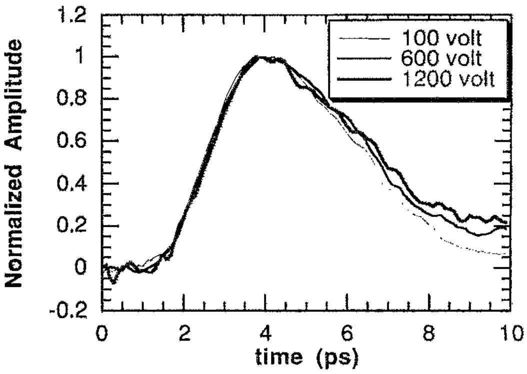

FIG. 5. Pulse shape as a function of applied bias for an optical energy of 900 nJ.

field, and wavelength. This process will cause current to persist until all carriers transfer back to the central valley where they either are trapped or recombine.

In conclusion, we report on the application of LT-grown GaAs for photoconductive switching using a pulse bias technique leading to the generation of a 825 V pulse with 1.4 ps rise time and duration of 4.0 ps. This represents the highest voltage ever obtained on the single picosecond time scale. This new capability to produce ultrashort high peak power electrical pulses is of interest for applications in fields such as nonlinear millimeter-wave spectroscopy, radar, high-energy physics, and ultrafast instrumentation.

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