High-speed InP optoelectronic switch with a tandem structure

Yoshikazu Hori,[a] Joel Paslaski, Maobin Yi,[b] and Amnon Yariv
California Institute of Technology, Pasadena, California 91125

(Received 12 October 1984; accepted for publication 28 January 1985)

A tandem-structure InP-optoelectronic switch has been fabricated and studied. This optoelectronic switch is capable of generating short electrical pulses, as well as varying the duration of electrical pulses between 40 and 400 ps (full width at half-maximum). The duration of the electrical pulses and the shortest pulse limit of the new switch are analyzed using a simple electrical model, and good agreement with experimental results has been obtained. The results indicate that the tandem-structure, optoelectronic switch can produce electrical pulses as short as the rise time of a single-structure switch, which is determined only by the electrical circuit time constant of the parallel switch capacitance and transmission line impedance.

Very high-speed electronic switches have recently been actively investigated for numerous applications such as high-speed electronic sampling gates and ultrafast pulse generators. With the development of the picosecond laser, photoconductive semiconductor optoelectronic switches under picosecond optical pulse illumination are thought to be the most promising and are the most actively studied for these purposes.

Previously studied means of increasing the response speed of optoelectronic switches include the use of amorphous material,[1] the introduction of deep levels either by doping with compensating impurities,[2,3] by radiation damage,[4] or by ion implantation,[5] surface treatment for increasing the surface recombination velocity,[6] the use of conducting materials,[7] and utilizing a longer wavelength erasing optical pulse. All of the above, except for the last means, cause a fast decay of the photogenerated carrier number thus, inevitably, causing a decrease in the efficiency of the switch by a reduction of the peak current. This happens not only because the high density of recombination centers causes low mobility and high on-state resistance, but also quick reduction of the switch conductance, following the optical pulse, begins to decrease the current before it saturates according to the circuit time constant. The utilization of a longer wavelength erasing optical pulse, proposed by Auston[8] in an early stage, provides a capability for generating and measuring electrical signals with a high time resolution. However, not only is a high intensity erasing pulse required, but also the choice of applicable semiconductor materials is more limited, and the efficiency of the silicon switch is quite low.

To obtain both a high speed and highly efficient optoelectronic switch, the combination of a highly efficient pulse generator with a negative pulse generator for pulse termination is considered to be a viable approach. Li *et al.* have used a pulse forming network whereby the negative pulse is provided by a reflection effected by the microstrip structure at a fixed time delay which determines the pulse width.[15] We have fabricated an InP optoelectronic switch with a tandem structure to obtain ultrashort electrical pulses without sacrificing peak current by utilizing the above new method. The characteristics and the limitations of the switch for the ultrashort electrical pulse production have been studied.

The switching device we have fabricated in this study is shown schematically in Fig. 1. The structure itself is similar to the device investigated by Auston[9-11] for the autocorrelation measurement of short electrical pulses. It consists of a microstrip transmission line (50 Ω) formed on Fe-doped semi-insulating InP with two gaps (40 μm) in the top metallization. A positive (V_+) and a negative (V_-) bias are applied to the first (right) and the second(left) microstrip lines respectively, and the output electrical signal is detected through the third (middle) transmission line. When the first gap, which is positively biased, is illuminated with a short and intense laser pulse, the photogenerated electron-hole plasma forms a conducting path across the gap, turning the first gap on. Then electrical current begins to flow toward the output electrode. After a time delay (tens to hundreds of picoseconds), the second gap, which is negatively biased, is illuminated with a second short and intense laser pulse, turning the second gap on. The resulting negative current is added, algebraically, to that of the first pulse causing the total current to be cut off quickly.

For the measurement reported here, a synchronously pumped mode-locked rhodamine 6-G dye laser[12] was used to illuminate the first and the second gaps. The pulse width of the dye laser is determined by autocorrelation measurements to be 3 ps (full width at half-maximum). A peak power of about 200 W at 590 nm was divided into two beams, and each was focused onto one of the two gaps. The delay time between the optical pulses was adjusted by a variable optical delay line. Bias voltages were provided through coaxial ca-

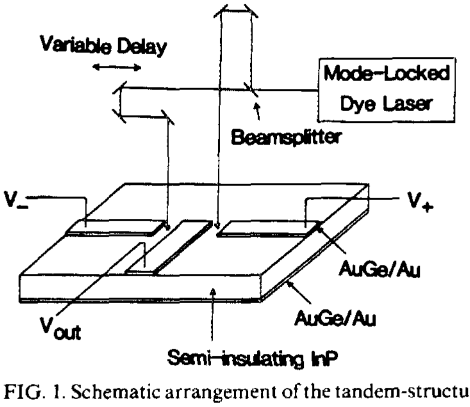

FIG. 1. Schematic arrangement of the tandem-structure InP optoelectronic switch.

---

[a] On leave from Matsushita Electric and Industrial Co., Ltd. in Japan.
[b] On leave from Jinlin University in People's Republic of China.

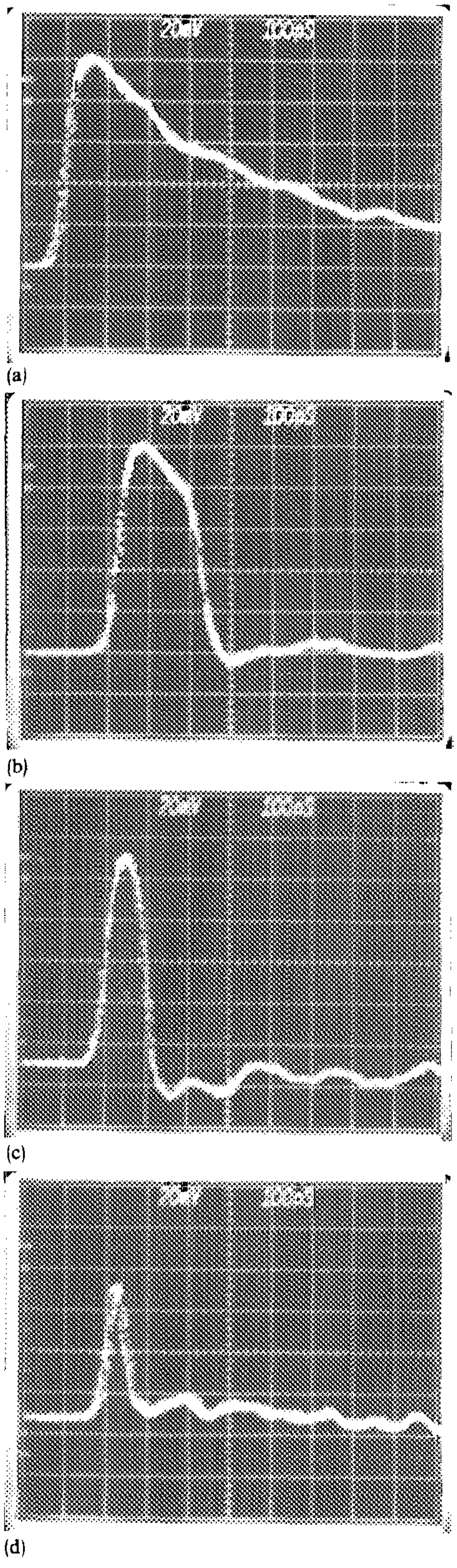

FIG. 2. Electrical pulse obtained experimentally from the switch. Delay times are (a) infinite, (b) 200 ps, (c) 100 ps, and (d) 40 ps. Positive bias voltage (V_+) is 3 V and negative bias voltage (V_-) is 0.6 V for (b) and 1.0 V for (c) and (d).

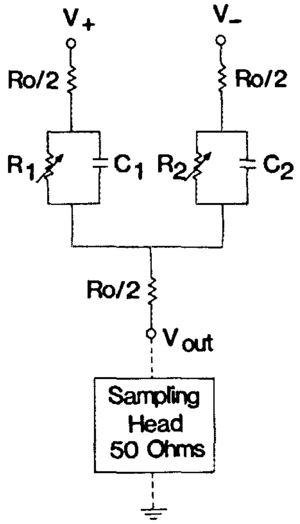

FIG. 3. Electrical model of the tandem-structure optoelectronic switch.

bles, and a sampling oscilloscope with a 25-ps rise time was used to monitor the device output.

The measured electrical pulses generated from the tandem-structure switch for various pulse delay times are illustrated in Fig. 2. The delay times (T_d) between the optical pulses are (a) $T_d = \infty$, in which case only the electrical pulse signal of a conventional single switch is observed, (b) $T_d = 200$ ps, (c) $T_d = 100$ ps, and (d) $T_d = 40$ ps. The positive bias is 3 V and the negative bias voltage is 3 V for (a), (c), (d) and 1.8 V for (b). With the decrease of the delay time T_d, the electrical pulse width decreases while its peak current remains constant until finally, at $T_d = 40$ ps, an electrical pulse of about 50 ps and 1.2 mA/3 V can be obtained [Fig. 2(d)]. The efficiency of the switch is higher by a factor of 5 than that of the switch based on radiation damaged silicon-on-sapphire, which is one of the fastest optoelectronic switches. However, it has been found that a 40-ps (FWHM) pulse width is the limit in our experiment, since when T_d was less than about 50 ps the output pulse height was decreased without decreasing the pulse width.

To clarify the lower limitation of the electrical pulse duration in the switch, a simple model has been considered, which is depicted in Fig. 3. In this model, each gap region is modeled by a combination of a variable resistor (R_1, R_2), which depends on the light intensity and a parallel capacitance (C_1, C_2). Connections to the gaps are made by 50-Ω transmission line. The capacitance of the gap (C_1, C_2) is assumed to be 0.2 pF. According to the microstrip theory,[13] the gap capacitance is expected to be less than 0.04 pF; however, our experimental result by measurement of the frequency dependence of S parameters was between 0.2 and 0.4

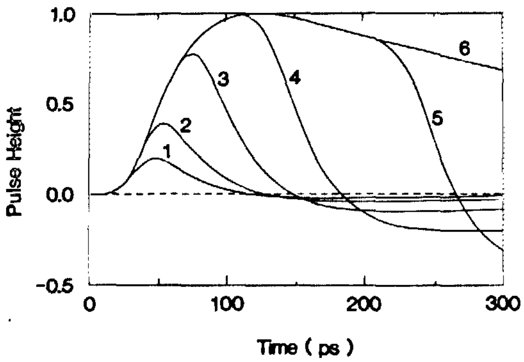

FIG. 4. Calculated results of the output electrical signal. All the curves are normalized by the peak value of the $T_d = \infty$ pulse. Parameter is the delay time: (1) $T_d = 10$ ps, (2) 20 ps, (3) 50 ps, (4) 100 ps, (5) 200 ps, and (6) $T_d = \infty$.

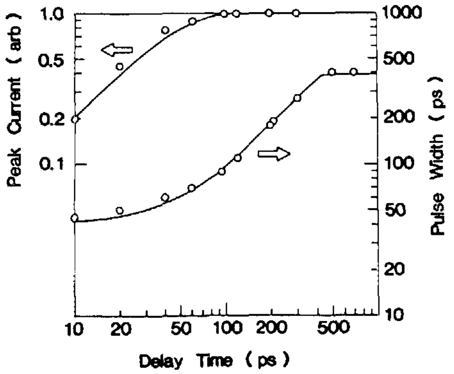

FIG. 5. Dependence of pulse width and pulse height on delay time. The lines denote the calculated results and circles plotted denote the experimental results.

pF. This value is also found to be reasonable in order to explain the rise time of the measured electrical pulses [Fig. 2(a)]. The conductance of the gaps is assumed to increase from zero to 1 $(k\Omega)^{-1}$ in 3 ps as estimated from our experimental results, and then decrease exponentially due to the carrier recombination in the bulk and surface. The carrier lifetime, determined from the decay curve of the single switch [Fig. 2(a)], is taken to be 350 ps.

The output pulse shape $V_0(t)$ of the switch is obtained by solving two second order differential equations numerically. Figure 4 shows the calculated results of the convolution of $V_0(t)$ and the 25-ps response curve.[14] In Fig. 4, the peak current for the long delay time is used as a normalization, in order to demonstrate the variation of the peak current as well as the electrical pulse width with the delay time. The delay time is changed between 10 and 300 ps.

According to the results, when the delay time (T_d) is large enough the pulse width is decided mainly by T_d, while the peak current is essentially independent of T_d. However, when T_d is relatively small the peak current will decrease with T_d, while the pulse width stays about 40 ps. These calculated results agree well with our experimental results including the observation that the pulse width saturates at short T_d. The shortest pulse width is decided by the time constant for charging or discharging the gap capacitance. Qualitatively, when the second optical pulse arrives very shortly after the first, the capacitor of the first gap is still being discharged and electrical current is increasing so the negative electrical current through the second gap cannot compensate it until it exceeds the first positive current. This time duration will give the shortest pulse width and is thought to be almost the same value as the time constant to charge or discharge the capacitance through the transmission line.

The relation between the pulse width and peak current of the electrical pulse generated and the delay time between the two optical pulses is shown in Fig. 5. The solid curves are calculated from our model while the experimental results are plotted as circles in the figure. The good agreement between theory and experiment lends credence to the viability of the model.

The reasonable success of the simple circuit model in accounting for the main characteristics of the tandem switch encouraged us to explore the question of the minimum pulse width achievable with such a switch. The model predicts that with further reduction of the gap capacitances (C_1,C_2) and on-state gap resistances (R_1,R_2), it should be possible to generate higher peak electrical pulses with durations of less than 10 ps.

In summary, we have demonstrated a tandem optoelectronic switch based on InP capable of generating variable width, high efficiency electrical pulses of widths as short as 40 ps. These are limited by the electrical circuit time constant and can in the future, be made considerably shorter.

This work was supported by the National Science Foundation.

[1] D. H. Auston, P. Lavallard, N. Sol, and D. Kaplan, Appl. Phys. Lett. **36**, 66 (1980).
[2] Chi H. Lee, Appl. Phys. Lett. **30**, 84 (1977).
[3] F. J. Leonberger and P. F. Moulton, Appl. Phys. Lett. **35**, 712 (1979).
[4] P. R. Smith, D. H. Auston, A. M. Johnson, and W. M. Augustyniak, Appl. Phys. Lett. **38**, 47 (1981).
[5] A. G. Foyt, F. J. Leonberger, and R. C. Williamson, Appl. Phys. Lett. **40**, 447 (1982).
[6] R. H. Moyer, P. Agmon, T. L. Koch, and A. Yariv, Appl. Phys. Lett. **39**, 266 (1981).
[7] J. Degani, R. F. Leheny, R. E. Nahory, M. A. Pollack, J. P. Heritage, and J. C. DeWinter, Appl. Phys. Lett. **38**, 27 (1981).
[8] D. H. Auston, Appl. Phys. Lett. **26**, 101 (1975).
[9] D. H. Auston, A. M. Johnson, P. R. Smith, and J. C. Bean, Appl. Phys. Lett. **37**, 371 (1980).
[10] P. M. Downey, D. H. Auston, and P. R. Smith, Appl. Phys. Lett. **42**, 215 (1983).
[11] D. H. Auston, IEEE J. Quantum Electron. **QE-19**, 639 (1983).
[12] T. L. Koch, L. C. Chiu, and A. Yariv, J. Appl. Phys. **59**, 6047 (1982).
[13] M. Maeda, IEEE Trans. Microwave Theory Tech. **MTT-20**, 390 (1972).
[14] W. Margulis and S. Laval, Appl. Phys. Lett. **40**, 892 (1982).
[15] K. K. Li, J. R. Whinnery, and A. Dienes, SPIE Proc. **322**, 124 (1982).