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# Light effect transistors for high speed and low energy switching and beyond

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**Abstract.** A semiconductor nanowire based photo-conductive device, referred to as light effect transistor (LET), is demonstrated for replicating the field effect transistor (FET) functions with potentially higher speed and lower switching energy, and offering novel, beyond FET functionalities, e.g., optical logic gates and optical amplification. In an integrated photonic circuit, photonic components are typically used for interconnection between electronic sub-systems. A hybrid electronic-photonic integrated circuits with LETs with FETs on one chip can take the advantages of the two worlds and mitigate their shortcomings, which will offer major improvement in performance over the pure electronic version.

## 1. Introduction

The phenomenon of photoconductivity is naturally used for photo-detection, but obviously can also be used for photo-electrical switching. However, using a photo-conductive (PC) device, referred to as light effect transistor (LET) (1), to replicate the functions of a modern electronic device, specifically, a field-effect transistor (FET) requires the consideration of somewhat different performance metrics. The output characteristic of a FET, source-drain (S-D) current  $I_{sd}$  vs. S-D voltage  $V_{sd}$  with varying the gate voltage  $V_g$ , can be readily reproduced by the corresponding characteristic of a PC device based on a metal-semiconductor-metal (M-S-M) structure by replacing  $V_g$  for the FET with an optical signal  $P_g$  for the PC device (2). The other important characteristic of the FET, transfer characteristic, i.e.,  $I_{sd}$  vs.  $V_g$  with varying  $V_{sd}$ , has its equivalence in the LET as  $I_{sd}$  vs.  $P_g$  with varying  $V_{sd}$ . For the FET, a device parameter called sub-threshold swing  $S$ , typically 70 mV/decade, from the superlinear region (before reaching the linear region) of the transfer characteristic is pertinently important for the switching energy. There is not a direct corresponding parameter for the PC device, since the superlinear region of the equivalent transfer characteristic for a PC device is usually not much of interest. However, for the LET application, we introduce a corresponding parameter  $S_L$  that measures the steepness of the  $I_{sd}$  vs.  $P_g$  curve under a given  $V_{sd}$ . Not only  $S_L$  is important for the optical switching energy but also for its novel applications under multi-beam gating operation. For the switching application, it is highly desirable for the LET to have a low dark current and small  $S_L$ , which translates to requiring the material to have a low dark carrier density and low defect density.

## 2. Prototype LET devices

Prototype LET devices were fabricated using CdSe nanowires. The LET basic characteristics are characterized under the illumination of one-beam [1]. For example, a device based on a CdSe nanowire



of  $5.5\mu\text{m}$  in length and  $80\text{ nm}$  in diameter yielded these typical results when illuminated by a focused laser beam at  $532\text{ nm}$  with a  $50\times$  lens of  $\text{NA} = 0.5$ : under  $V_{\text{sd}} = 1.43\text{ V}$ , a dark current around  $1\text{ pA}$ ,  $S_L$  around  $3\text{ nW/decade}$  (applied power, only partially absorbed),  $I_{\text{sd}} = 0.35\text{ }\mu\text{A}$  at  $P_g = 0.11\text{ }\mu\text{W}$ . The output and transfer characteristic of this LET are shown in Fig 1. These results allow us to assess the LET potential. The typical carrier lifetime of II-VI semiconductors is around  $100\text{ ps}$  at room temperature. Using these device parameters, the optical switching energy would be in the order of  $E_{\text{op}} \approx 0.01\text{ fJ/switch}$ , the electrical switching energy would be around  $E_{\text{el}} \approx 0.05\text{ fJ/switch}$ , and  $E_{\text{tot}} \approx 0.06\text{ fJ/switch}$ . These are already better than typical FETs having switching energy of  $0.1\text{--}1\text{ fJ/switch}$ . In principle, the LET performance can be much better than that of this relatively large prototype device. For a shorter device in the ballistic transport region (e.g.,  $L \leq 100\text{ nm}$ ), the carrier velocity will be in the range of  $(1\text{--}10)\times 10^7\text{ cm/s}$ , which implies a carrier transit time or switch time in the order of  $0.1\text{--}1\text{ ps}$ . If we consider an idealistic device of  $100\text{ nm}$  long operating in the ballistic region with a quantum impedance of  $12.9\text{ k}\Omega$ , transit time of  $0.1\text{ ps}$ ,  $I_{\text{sd}}$  of  $1\text{ }\mu\text{A}$ , and no voltage loss at the contacts, the electrical switching energy could be as low as  $1.3\times 10^{-21}\text{ J/switch}$ . Therefore, LETs can potentially be used as ultra-fast (THz) switches with an extremely low switching energy.

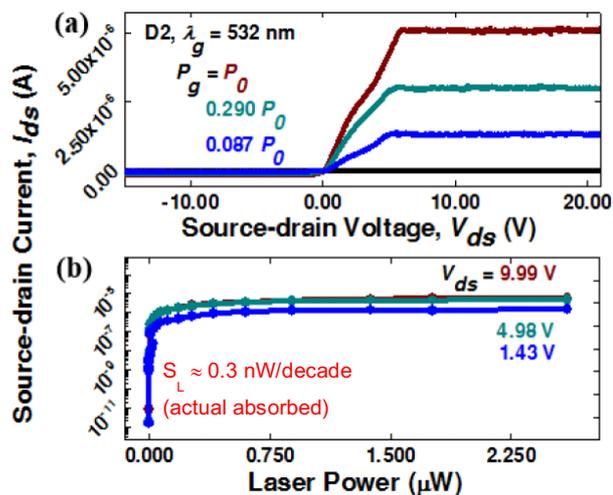


Fig. 1 The output (a) and transfer (b) characteristic of a CdSe nanowire based LET with  $P_0 \approx 1.4\text{ }\mu\text{W}$  (applied power).

### 3. LETs gated by multiple beams

Besides replicating the basic functionalities of a FET, an LET is uniquely capable of operating under multiple independent gating controls for optical logic and optical amplification. It functions as an OR gate if multiple light beams with powers falling in the saturation region of the transfer characteristic, as show in Fig. 1(b). However, it is particularly interesting to operate an LET in its sub-threshold, i.e., the superlinear region. Fig 2 offers an example of two beam gating for the same device, using one  $532\text{ nm}$  laser beam and one white light source. In the sub-threshold region, for the logic application, the LET functions as an AND gate: individually the weak optical beams A and B generate very small photo-currents barely above the noise level, which can be taken as the “0” state; but together they generate a photo-current that is much greater than the sum of the signals generated by the two beams individually (explicitly 48 times of the beam A alone), which can then be viewed as the “1” state. For the interest of analog application here photo-detection, one can view the beam A as the light signal to be detected, and the beam B serving the amplification role, which effectively makes a barely detectable signal A readily detectable.

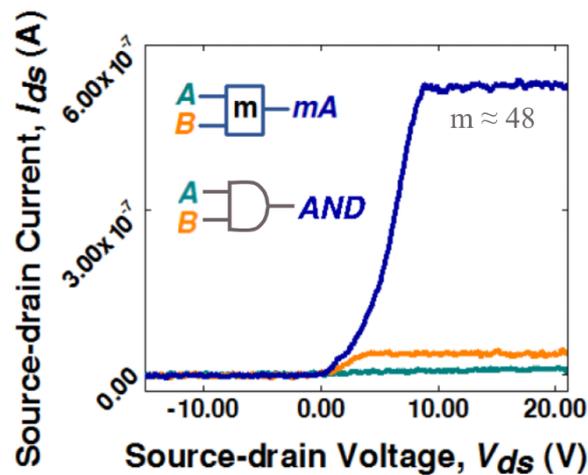


Fig. 2 Demonstration of two beam gating of an LET.

#### 4. Concluding remarks

Lately photonic-integrated circuits (PICs) are receiving a great deal of interest. It is now possible to integrate a large number of electronic devices and photonic components on a single chip to perform logic, memory, and interconnect functions [3]. However, in an integrated photonic circuit, photonic components are typically used for interconnection or passing information between electronic sub-systems. LET provides a new platform for future generation computing related applications by taking advantage of unique functionalities originating from the integration of electronic and optical properties in the single device level. It is further possible to form a hybrid electronic-photonic integrated circuit consisting of both electronic elements and photonic elements that work more closely together in data processing as opposed to the situation in the common PIC.

However, to achieve the higher level integration, there is a major challenge that is related to the mismatch between the wavelength of light and the size of the electronic device. Specifically, it is practically impossible, at least in a foreseeable future, to make a light source with a foot print down to the comparable size of a modern FET, which affects the energy-data rate [4]. Another major issue is the inconvenience of using the output of one logic gate made out of LETs to drive the next LET based logic gate without going through relatively inefficient electronic to optical energy conversion. To mitigate these challenges and explore the advantages of LETs more directly in computing applications, we should seek the opportunities in the conventional integrated circuits where some FETs only serve the roles of switching a circuit on and off, and a group of them are required to be gated simultaneously.

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