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Silicon nanocrystal light emitting device as a bidirectional optical transceiver

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Abstract

An all-silicon light emitting and detecting device is described here. It is based on a nanocrystalline-silicon light emitting diode (Si-NC LED). The Si-NC LED has up to 0.2% external power efficiency, when forward biased, while it has a photoresponsivity of up to 1 mA W^{-1} when reverse biased. Therefore, the very same device can be used as a transmitter and receiver node of an optical link. We demonstrate a power loss of 10^{-3}% and a modulation speed of up to 10 kbit s^{-1} by connecting two Si-NC LEDs by a multimode optical fiber.

(Some figures in this article are in colour only in the electronic version)

Silicon photonics is a demonstrated technology to enable interchip or intrachip optical interconnects [1–3]. Optical links able to send 50 Gb s^{-1} over 200 m span have been fabricated [4]. The actual implementation of the light source and of the detector in silicon photonics is based on a heterogeneous approach where a III–V semiconductor acts as an active laser material and a Ge semiconductor as an active detector material [5]. Therefore, there is still an interest to evaluate the potential of an all-silicon approach for optical interconnects. This could have lower performances, which implies other than high-speed interconnect applications, but should be cheaper and easier to fabricate within a standard CMOS factory. Among different possibilities, silicon nanocrystals (Si-NC) show interesting optoelectronic properties [6]. Si-NC-based light emitting diodes (LEDs) have been fabricated with standard CMOS processing. The power efficiency of Si-NC LED is still an order of magnitude lower than the III–V-based LED one. However, it is of interest to investigate whether Si-NC LED can be used as one node of an optical link. Here, we study a Si-NC LED which is used as a light emitter as well as a light detector in an optical link (figure 1).

The Si-NC LED structure is formed of a metal oxide semiconductor capacitor where five alternating stoichiometric SiO_2 and silicon-rich oxide (SRO) layers are used as the active material which replaces the gate oxide (inset of figure 1). The nominal thickness of SRO and of the oxide layers within the multilayer (ML) stack is 3 and 2 nm, respectively. Silicon nanocrystals were formed by annealing the ML at 1150 °C for 30 min in nitrogen atmosphere. The ML was deposited on a Si p-type wafer.

When the Si-NC LED is forward biased (gate negative), an external power efficiency of up to 0.2% and an emission peak centered at about 750 nm are observed (see [7] for more details). When illuminated, the Si-NC LED shows a photovoltaic effect [8]. In addition, when reverse biased (gate positive) the Si-NC LED behaves as a photodector for visible/infrared light (from 400 to 1100 nm) with an average photoresponsivity[3] of about 1 mA W^{-1}.

Figure 2 shows the optoelectronic properties (electroluminescence and photoresponsivity) of a characteristic Si-NC LED. The electroluminescence spectrum is measured under a forward bias of −5 V (grounded at the bottom of the LED). The photoresponsivity spectrum of the Si-NC LED is measured for a reverse bias of 5 V. It could be noted that the emission spectrum under forward bias matches the high-photoresponsivity region. In fact, two different device regions are responsible for the two different responses: the electroluminescence is due to the emission of the Si-NC, while the photoresponse is due to absorption in the silicon

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[3] Photoresponsivity is measured by illuminating the receiver and measuring the generated photocurrent under a reverse bias of 5 V from top to bottom contact. The resolution in wavelength is given using a xenon lamp through a single grating monochromator.

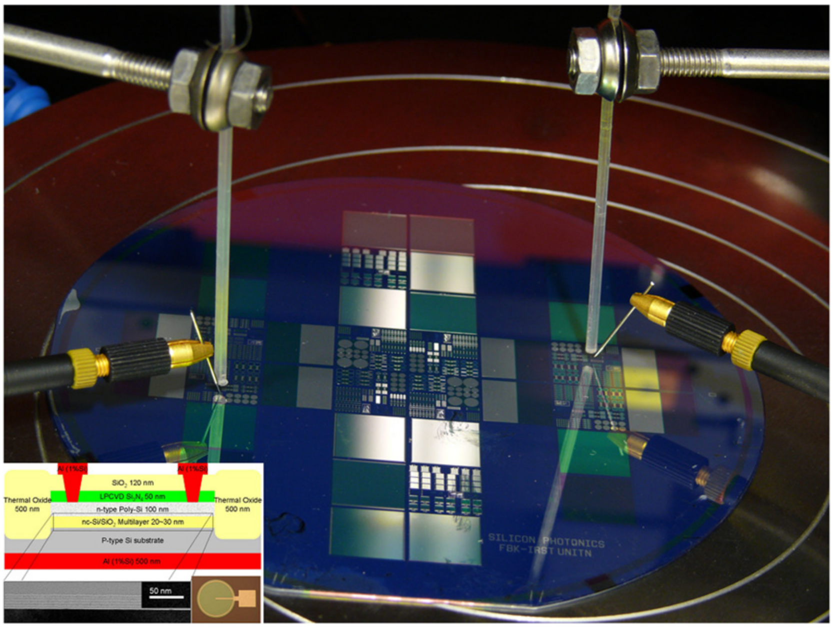

Figure 1. Image of the transceiver. The electrical signals are transmitted and collected by the top contacts, the chuck provides the reference bottom contact. The optical signals are transmitted through a 1 mm core optical fiber coupled on top of the devices. Device schematic cross section and top view of the device (inset).

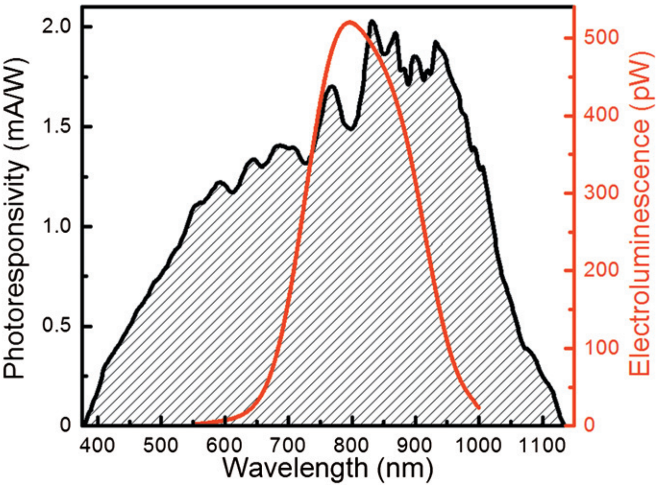

Figure 2. Filled area: photoresponsivity of the device in the detection mode, reverse biased at 5 V. Empty area: electroluminescence of the device in the emission mode, forward biased at −5 V.

substrate. This combination has an advantage with respect to other all-silicon approach for transceivers since the emission wavelength is spectrally separate from the absorption band edge. As an example, Zhao *et al* [9] reported an optical link between two similar silicon diodes. The performances of the link were limited by the fact that emission occurs at the silicon absorption band edge.

We realized an optical link between two equal 300 μm diameter Si-NC LEDs by coupling a multimode 1 mm core plastic fiber on the top of the surface emitting LED. Coupling losses (L_C) between the LED and the fiber are estimated to be 3 dB. We tested two different configurations where the two LEDs are part of two different dies (i.e. electrically isolated and physically separated) or are on the same wafer (i.e. only electrically isolated, see figure 1). No differences in the results have been found. We forward bias one of the LEDs and reverse bias the other LED. The results are not dependent on the choice of the LED. Both LEDs can work as a receiver or as a transmitter; this is the reason why we call the single LED a transceiver. Figure 3(*a*) shows the receiver photocurrent and the optical link efficiency as a function of the transmitter bias. The transmitter bias was scanned from 0 to −6 V, while the receiver LED was kept at a constant reverse bias of 5 V. A significant receiver current is observed when the transmitter bias is larger than −2 V. Figure 3(*b*) shows the transmitter electroluminescence and transmitter power efficiency as a function of the transmitter bias. It is observed that the photocurrent is almost linear with the electroluminescence, that is the receiver has a constant photoresponsivity. On the other hand, the transmitter power efficiency is strongly dependent on the transmitter bias. From the ratio of the electrical power generated at the receiver (P_R) to the electrical power dissipated by the transmitter (P_T), we calculate the efficiency (η) of the optical link:

$$\eta = \frac{P_R}{P_T} = \frac{i_R V_R}{P_T} = \frac{\Re P_R^0 V_R}{P_T} = \frac{\Re L_C L_P L_C P_T^0 V_R}{P_T}$$
$$= \frac{\Re L_C L_P L_C \eta_T P_T V_R}{P_T} = \Re L_C L_P L_C \eta_T V_R \approx 5 \times 10^{-4}\%,$$

where i_R and V_R are the photocurrent and the reverse bias of the receiver, $\Re = 2$ mA W^{-1} and P_R^0 are the photoresponsivity and the optical power reaching the receiver, L_C and $L_P = 0$ dB are the coupling and the fiber losses, P_T^0 and $\eta_T = 0.2\%$ are the transmitter emitted power and the transmitter power efficiency, respectively. The estimate agrees with the measured data as is evident from figure 3. Note that in figure 3, P_R is calculated as the total power measured at the receiver

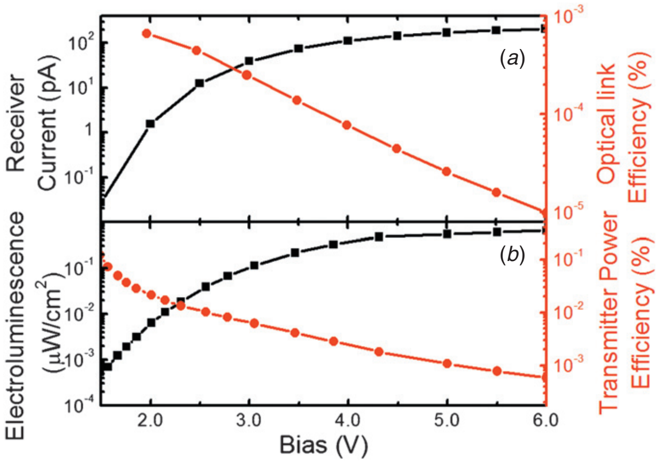

Figure 3. (*a*) Receiver photocurrent (squares) and optical link efficiency (circles) as a function of transmitter bias; (*b*) transmitter electroluminescence (squares) and transmitter power efficiency (circles) as a function of transmitter bias.

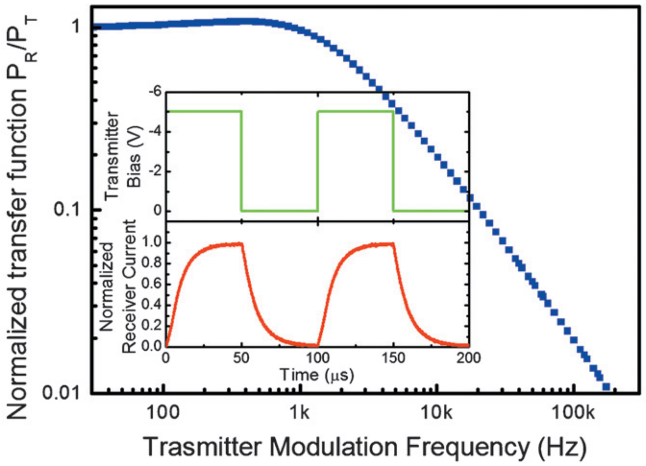

Figure 4. Normalized transfer function as a function of transmitter modulation frequency; inset: electrical bias of the transmitter (top) and electrical output of the receiver (bottom) as a function of time.

($P_{R,\text{tot}}$) minus the measured power in dark condition ($P_{R\text{dark}}$): $P_R = P_{R,\text{tot}} - P_{R,\text{dark}}$. From figure 3 it is also clear that when the driving bias is increased, the link efficiency drops due to the decrease of the power efficiency of the transmitter. It is also important to emphasize that the system shows a good stability over time particularly with respect to the emitter that is most affected by stress (see [10] for more details).

Figure 4 shows the frequency response of the optical link. We drove the transmitter under square-wave forward bias (0,−5 V) and variable frequency. The ac characteristics of the transmitter can be found in [9]. A trans-resistive amplifier (50 Ω resistor) was used to measure the receiver signal with an oscilloscope operated in the alternate current coupling. A typical lineshape is reported in the inset of figure 4. The receiver current follows the modulation of the transmitter bias. The cut-off frequency (3 dB frequency) is at 3.3 kHz which is mainly due to the frequency limit of the transmitter [11]. However, still at 100 kHz we are able to measure a modulated receiver current, though very weak.

An estimate of the power per bit needed to run the optical link can be found by the following arguments. Since the transmitter is switched on/off, while the receiver is always on, the power is dissipated during the on state (sending a bit) for the transmitter and during the waiting time for the receiver (when illuminated the receiver generates electrical power). The injected current in the transmitter at the −5 V bias is 50 μA. If we consider a 10 kHz frequency, i.e. a 50 μs bit width, the dissipated power by the transmitter is 125 μW. On the receiver side, the bias is fixed at 5 V which corresponds to an injected current of 50 fA under dark condition, so the maximum dissipated power is 250 fW. Therefore, the main contribution to the dissipated power comes from the transmitter. Thus, 125 μW per bit corresponds to an energy per bit of 1.25 μJ bit^{-1}.

In conclusion, we demonstrated an optical link based on a silicon nanocrystal device operated as a bidirectional transceiver. The link performances have been evaluated and found suitable for niche applications where the most important metrics are integrability and low cost, e.g. for lab-on-a-chip applications or for slow data communication in consumer electronics. Indeed, the performance of the optical link is not at all comparable to the state-of-the-art interconnect technology available in silicon photonics.

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