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Power efficiency estimation of silicon nanocrystals based light emitting devices in alternating current regime

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The power efficiency of silicon nanocrystal light-emitting devices is studied in alternating current (ac) regime. An experimental method based on impedance spectroscopy is proposed. The power efficiency in ac regime is higher than the one measured in direct current before a threshold frequency and decreases significantly for higher frequencies. This decrease is attributed to an increase in electrical power injected at high frequencies and it is directly related to the disordered microscopic structure of the active material. The proposed method can be applied for any kind of device for which it is possible to measure the impedance characteristic. © *2011 American Institute of Physics*. [doi:10.1063/1.3592566]

There is currently strong interest in developing silicon-based light emitting sources which can be integrated in photonic circuits. One approach is based on the realization of nanocrystalline silicon light emitting devices (Si-NC LEDs) directly on the silicon substrate. Alternating current (ac) light modulation with these devices is a way to produce data stream for on-chip optical networks. In addition, ac driving is also believed to increase the efficiency of these devices. In most of the works in which the AC power efficiency measurements, the value of power efficiency is not quoted[1–4] or the accuracy of its estimation is unclear.[5] This is mainly due to the difficulty to measure the low currents flowing through the devices and it is complicated by the driving frequency values.[6] In ac regime, the electroluminescence (EL) as a function of driving frequency shows a dependence similar to those in Fig. 1(b). It is observed that the EL increases significantly as the frequency increases, it reaches a maximum and then it decreases. In the literature,[1–5] this increase in EL is attributed to an efficiency increase while the decrease, at higher frequencies, is attributed to the Auger suppression of EL due to the finite exciton recombination lifetime.

The purpose of this letter is to study in more details the efficiency in ac regime by measuring the injected electrical power with accuracy. For this reason we developed an experimental method to estimate the efficiency based on large-signal impedance spectroscopy.

The device used in this work is a multilayer silicon nanocrystal based metal-oxide-semiconductor (MOS) LED which shows high dc efficiency.[7] The active material is composed by 5 layers of 3 nm thick silicon-rich-oxide (SRO) separated by layers of 2 nm thick SiO_2. The layout, fabrication, and optoelectrical characteristics can be found elsewhere.[8,9] Very similar results to those discussed in this work have been obtained also on other devices with different active layer compositions. For the sake of clarity, here we discuss only this representative device.

In order to estimate the electrical power injected under a sinusoidal modulation, we consider the values of the time dependent voltage (V) and current (I) which are defined by the applied waveform and by the reaction of the device. In the case of a sinusoidal waveform, the dissipated electrical power is given by the average electrical power, i.e.: $P_{ac} = V_{rms} I_{rms} \cos \varphi$. V_{rms} and I_{rms} are the root mean square val-

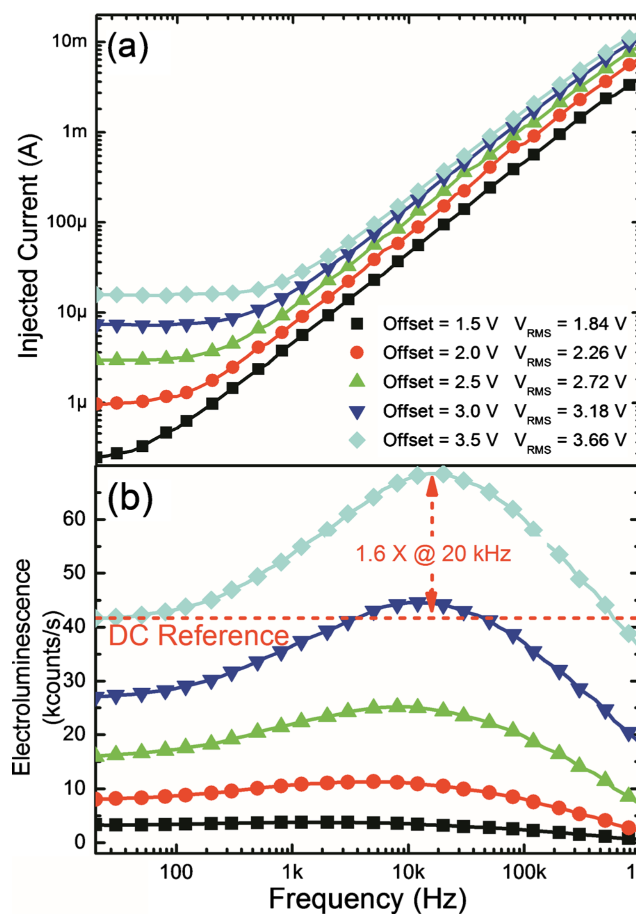

FIG. 1. (Color online) (a) Estimated rms injected current as a function of frequency and different offsets applied and (b) EL as a function of frequency. The MOS-LED is biased by a sinusoidal waveform. The dc reference is measured with a dc bias equal to 3.66 V.

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ues of V(t) and I(t) and φ is their relative phase shift. While V_{rms} is easily calculated from the driving bias, I_{rms} estimation is difficult because of the typical reactive characteristic of the device (spikes, distortions, etc.), its low value and the frequency range of the applied signals. A way to circumvent this problem is to measure the device complex impedance, $Z(\omega,V)$, as a function of angular frequency, ω, in the interested range of frequencies and signals, and then, by applying the generalized Ohm's law, to calculate I_{rms}. The injected electrical power in ac regime can be written as $P_{ac} = V_{rms}^2/|Z|\cos\varphi$, where φ is the phase of Z.

We studied a wide range of modulations conditions (different waveforms, different peak-to-peak voltages, and different offset voltages), geometrical factors (different devices area and shapes), and material properties (SiO_2 barrier thickness and SRO thickness). In this work, we discuss results obtained with sinusoidal waveform of a fixed peak-to-peak voltage (V_{pp}) value of 3 V and for different offset voltages as a representative set. Figure 1(a) shows I_{rms} for different offset voltages. The range of offsets (from 1.5 to 3.5 V) is determined on the basis of the EL turn-on dc voltage of 2 V and of the maximum driving voltage before device failure of 5 V. The measurements show an increase in injected current of few orders of magnitude as a function of frequency. During the frequency scan, V_{rms} was kept constant. Thus, the maximum enhancement of the ac EL by a factor of 1.6 [Fig. 1(b)] cannot compensate the increase in injected power, as we will show later. Consequently, the power efficiency decreases. More in details, Fig. 1(a) shows that the dependence of the current on the frequency is first constant and then rises rapidly. The frequency range of the flat part depends on the voltage offset. This is due to the fact that the span in voltage, during a modulation period, covers different region of the I-V characteristics.

More insights can be obtained by looking at the impedance characteristics of the device. As an example, Fig. 2(b) shows the characteristics when the EL is the strongest: offset of 3.5 V and $V_{rms}=3.66$ V. The impedance is well fitted by a parallel combination of a resistor (R) and a constant phase element (CPE).[10] The impedance of CPE is defined as $Z_{CPE} = 1/T(j\omega)^{\alpha}$, where T is a constant (with units F $s^{\alpha-1}$), ω the angular frequency and α ($-1 \le \alpha \le 1$) is related to the angle of rotation of a purely capacitive line on the complex plane plots.[10] The fitting model impedance is thus $Z=R/[1+(j\omega\tau)^{\alpha}]$, where $\tau=(TR)^{1/\alpha}$. CPE has been considered to represent a circuit complex element with limiting behavior as a capacitor for $\alpha=1$, a resistor for $\alpha=0$ and an inductor for $\alpha=-1$. In our case α is about 0.95 which means that the CPE describes a system with an average behavior similar to a distributed capacitor or a transmission line network. Practically, this model describes, in a compact way, a network of RC elements connected together.[11] The RC network is thus representative of the various Si nanocrystals (the capacitors) and of the leakage current paths (the resistors). At low frequencies, a weak current flows through the resistor network via one or more percolation paths, which connect the various nanocrystals. Injection into the Si-NCs looks like the charging of a capacitor. Indeed Si-NCs are used as storage elements in memories. At high frequencies, charging and discharging of the capacitors, formed by separately charged nanocrystals, dominate the conductivity: in this regime high current can flow at the expenses of the bipolar injection into

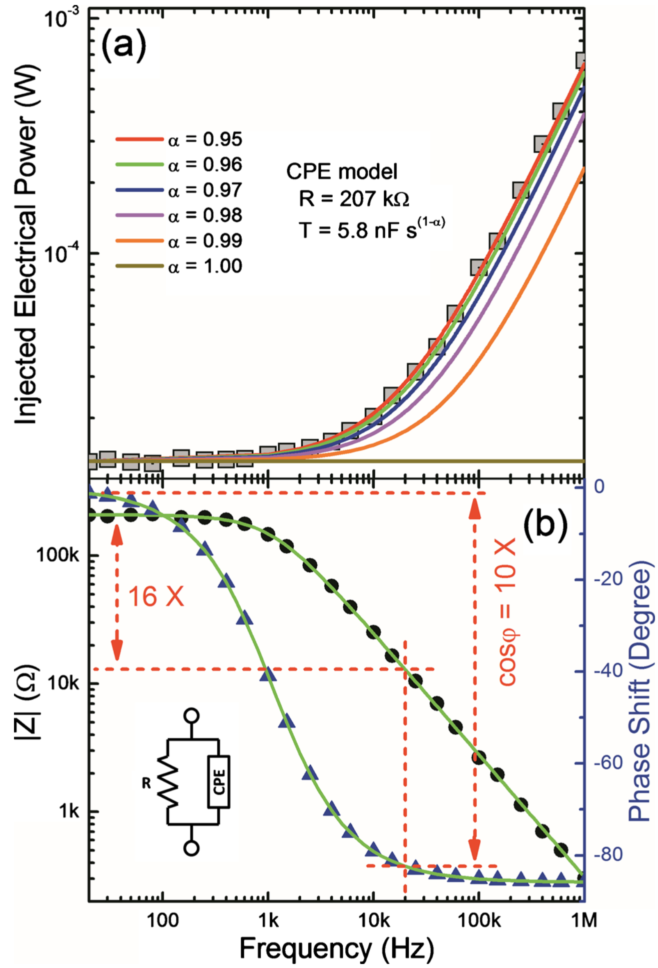

FIG. 2. (Color online) (a) (Squares) Estimated injected electrical power; (lines) CPE model fits as a function of α value; (b) (dots) module of complex impedance characteristics as a function of frequency; (triangles) phase of complex impedance as a function of frequency; (lines) fit of the data by R-CPE parallel equivalent model (inset): $R=207.2\pm0.7$ kΩ, $T=5.8\pm0.3$ nF $s^{-0.05}$, and $\alpha=0.95\pm0.01$. Measurement data are for an offset=3.5 V and $V_{rms}=3.66$ V.

the silicon nanocrystals. This explains the decrease in the EL power efficiency while the injected current increases. Another way to look at this problem is to consider the active layer as a composite with phases of different conductivities which has an average conductivity which increases with frequency.[11] This is because the space over which carriers move is determined by the frequency: the span is short at high frequency while it is long at low frequency. Thus, at high frequency the charge carriers move in high conductivity regions, while at low frequencies charge transport is limited by bottlenecks of poorly conducting regions. On the considered range of frequencies, from 20 Hz to 1 MHz, the module of impedance decreases by three orders of magnitude with increasing frequency and the phase shift changes from 0° to 85° [Fig. 2(b)]. With these values the dissipated electrical power increases by about 70 times as a function of frequency [Fig. 2(a)]. It is also interesting to note that a pure RC model ($\alpha=1$) cannot fit the data since it yields a constant power as a function of frequency.

During the impedance characterization we measured also the spectrally integrated (400–1000 nm) EL. Thus, with one single measurement, we have all the parameters to estimate the power efficiency in ac regime: V_{rms}, I_{rms}, φ and P_{opt}.

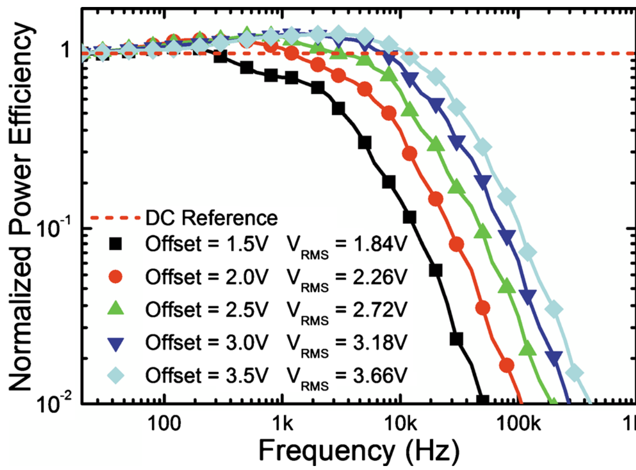

FIG. 3. (Color online) Normalized power efficiency as a function of frequency and different applied offsets; power efficiency level in dc at $V_{dc}=V_{rms}$ (horizontal dashed line), the absolute dc power efficiency is 0.05%.

When $V_{rms}=3.66$ V and offset=3.5 V, the EL increases by 1.6 times from the low frequencies value, quasi-dc regime, to the peak value, while I_{rms} increases by three orders of magnitude. Since V_{rms} was kept constant, the power efficiency decreases. To define the starting point dc value, we set $V_{dc}=V_{rms}$ and confirm that the EL intensity is the same for the two measurements. Finally, Fig. 3 shows the power efficiency in dc (as a level) and in ac as a function of frequency for different offsets. The dc level is reached for quasi-dc regime. As the frequency increases, the power efficiency slightly increases and then dramatically decreases. In dc regime, charge transport is dominated by the tunneling among Si-NCs and by the accumulation of charges at interface states at the contacts/active material interface. The charge accumulation screens the applied electric field and decreases the effective injection. When the LED is driven in ac, the mean amount of accumulated charges decreases and the injection becomes more efficient. In this case, the bias modulation enhances the efficiency. Figure 3 shows that at an offset =3.5 V, the efficiency enhancement at 4 kHz is up to 50% of the dc value, while the EL intensity increase, at the same offset, is about 160% at 20 kHz [Fig. 1(b)]. Note that the EL is due to bipolar injection into the Si-NC, which means that the electron and hole have to be injected into the same Si-NC simultaneously. Low frequency means long distances that a carrier can cover, i.e., the probability that an electron encounters a hole into a Si-NC is large. For higher frequencies the efficiency decreases dramatically because the injected charges are constrained to move on short distances or in short dissipative paths. The encounter probability thus decreases and, in turn, the EL drops. It is thus evident that the efficiency in AC is governed by a competition between field screening, charge transport and dissipative processes. This occurs for frequencies where recombination is not lifetime limited.

We did other experiments by using different waveforms, area of the devices and material compositions. They show similar results to those discussed in this work. The main difference among the various bias conditions is the frequency at which the EL efficiency decreases below the dc value. This analysis suggests that, to increase the power efficiency, one has to keep the conductivity constant in a wide frequency range by working on the geometry (large area or smaller thickness) of the device and on the properties of the active material (large dielectric constant).

In conclusion, we presented an experimental method to estimate the power efficiency in ac regime of electroluminescent devices. We proposed a phenomenological model to explain the injection under ac driving. The analysis shows that the power efficiency depends on both geometrical properties of the device and intrinsic properties of the active material. It is shown that relevant properties are the charging of the Si-NCs, the span over which charge carriers can move, the encounter probability (bipolar injection) and the composite nature of the active material. The proposed method, which is based on the concurrent measurement of the current and of the EL, is quite general and can be applied to other kinds of light emitting devices.

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