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Fast switching of light-emitting diodes

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Abstract

We have proposed a method of increasing the switching speed of a light-emitting diode by controlling the voltage across the device rather than the current through it. While the speed of conventional current-control methods is limited by the recombination processes in the active region, with their characteristic time being of the order of several nanoseconds, we have shown both analytically and numerically, that the characteristic time of the voltage-control method can be two orders of magnitude smaller. Such a speed is provided by a large pulsed current that rapidly removes excessive carriers from the active region if the device is being switched off, and injects them into the active region if the device is being switched on.

One of the most important parameters of light-emitting diodes (LED) is their speed of operation or the response (switching) time. This time determines how fast a LED can be switched from one state characterized by the current I_1 and forward voltage U_1 to another one (I_2 and U_2). It is commonly believed that the response time of LEDs is limited principally by the lifetime τ of injected carriers that is responsible for radiative recombination. If we consider a small sinusoidal perturbation of the pumping current so that $I = I_0 + I_1 \cos(\omega t)$, the emitted optical power P varies linearly with injected current and can be written as $P = P_0 + P_1 \cos(\omega t)$. The associated transfer function, which is defined as $\mathscr{H}(\omega) = (P_1/I_1)\exp(j\phi)$, assumes the form [1]

$$\mathscr{H}(\omega) \propto \frac{1}{1 + j\omega\tau}, \tag{1}$$

which is the characteristic of a resistor-capacitor circuit. The rise time of the LED is τ and its 3-dB bandwidth is $B = (2\pi\tau)^{-1}$. A larger bandwidth B is therefore attained by decreasing τ, that includes contributions from both the radiative lifetime, which is estimated as $\tau_r = (C_{opt}n)^{-1}$, and the non-radiative lifetime τ_{nr}, through the relation $\tau^{-1} = \tau_r^{-1} + \tau_{nr}^{-1}$. However, reducing τ_{nr} results in an undesirable reduction of the quantum efficiency. Therefore, in the optimal regime of operation we can consider $\tau = \tau_r$, which is known to be of the order of several nanoseconds. Such characteristic times were reported for InGaN/AlGaN double heterostructure light-emitting diodes [2,3] for GaAs/AlGaAs LEDs [4,5], and for AlGaInP LEDs [6].

It has been stated in [7] that conventional methods of modulating semiconductor lasers by varying the pumping current are limited to relatively low frequencies of about 1 GHz ($\tau > 1$ ns) and smaller. Though the problem of fast control of laser diodes is more complicated due to the appearance of other characteristic time parameters like the relaxation oscillation frequency and the photon lifetime in the laser cavity, but the statement that a fast change in the pumping current does not lead to an as fast change in the emitted

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power, is still true. That is why there has been suggested several indirect methods of the light power modulation such as electron heating by an externally applied microwave field [8] or by an additional high-frequency signal [9,10], and electro-optic modulation of the Bragg reflectors in surface-emitting lasers [7].

So we can conclude that direct control of the pumping current in laser diodes and, especially, in LEDs fails to provide high speed of operation because a change in the emitted light power cannot occur until the excess carriers in the active region recombine.

However, it is known that a step-like switching of the voltage across a PIN diode [11,12] or thyristor [13] from the forward to reverse bias causes a pulse of reverse current I_R that is actually limited by a series resistance only. If this resistance is sufficiently small, the magnitude of the pulse can be much greater than the forward current I_F through the diode before the switching. This process is called the reverse recovery and its characteristic time is given by [11]

$$T_s = \tau \times \ln\left(1 + \frac{I_F}{I_R}\right). \tag{2}$$

Actually, the value of switching time determined from Eq. (2) is just an estimation, but the important fact is that for $I_R \gg I_F$, the switching time T_s can be considerably smaller than the recombination time τ if we control the voltage across the device rather than the current.

To demonstrate the proposed switching method on a model that allows a relatively simple analytical solution, we have considered a forward biased *pn*-junction diode with low injection level in both *p* and *n* regions. We assume that the current is caused by the diffusion of minority carriers and all the voltage drops across the junction only. The excess electron concentration in the *p* region is given by

$$n(x) = n_i e^{qV/kT} e^{-x/L} = n_0 e^{-x/L}, \tag{3}$$

where n_i is the equilibrium electron concentration in *p* material, $L = \sqrt{D\tau}$ is the electron diffusion length, D is the diffusion coefficient and τ is the lifetime of electrons in the *p* region. It follows from Eq. (3) that the concentration of electrons at the junction ($x = 0$) is determined by the bias voltage.

Let us suppose that the voltage across the junction and, consequently, the electron concentration is changed so that the new concentration at the junction is $n_0 - \Delta n$, where Δn is a given function of time expressed as

$$\Delta n(t) = \Delta n(1 - e^{-\alpha' t}), \tag{4}$$

where α' is a constant that determines how fast the concentration at the junction is changed. Under the assumptions, the deviation of electron concentration in the volume of the *p*-region from that defined by Eq. (3) is governed by the following equation:

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau}. \tag{5}$$

In dimensionless variables $t = t_{old}/\tau$ and $x = x_{old}/L$, Eq. (5) looks as follows:

$$\frac{\partial n}{\partial t} = \frac{\partial^2 n}{\partial x^2} - n. \tag{6}$$

The initial condition for this equation is $n(x, t = 0) = 0$, and the boundary conditions are $n(x = 0, t) = \Delta n(1 - e^{-\alpha t})$, where $\alpha = \alpha'\tau$, and $n(x = \infty, t) = 0$. Applying the Laplace transform to Eq. (6), we obtain

$$\frac{\partial^2 n_p}{\partial x^2} = (p + 1)n_p, \tag{7}$$

where $n_p(x)$ is the Laplace transform of the function $n(x, t)$.

The solution of Eq. (7) with the account of the initial and boundary conditions is:

$$n_p(x) = \Delta n e^{-x\sqrt{p+1}}\left[\frac{1}{p} - \frac{1}{p+\alpha}\right]. \tag{8}$$

Since the current in our system can be written down as

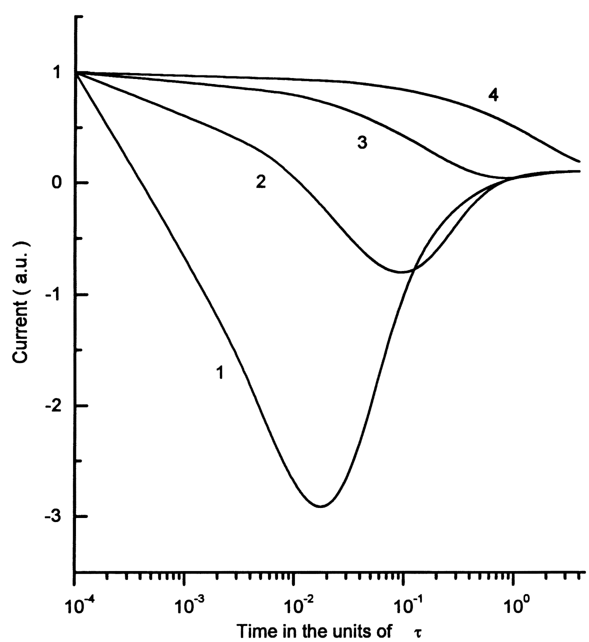

Fig. 1. Transient current vs time for voltage-control switching of the model *pn*-diode. The minority carrier concentration at the junction is given by $n(t) = n_0 - \Delta n(1 - e^{-\alpha t})$. The curves correspond to (1) $\alpha = 50$, (2) $\alpha = 10$, (3) $\alpha = 2$, and (4) $\alpha = 0.5$.

$$j(t) = -\frac{\partial n}{\partial x}\bigg|_{x=0}, \tag{9}$$

the Laplace transform of the current is

$$j_p = \Delta n\sqrt{p+1}\left[\frac{1}{p} - \frac{1}{p+\alpha}\right]. \tag{10}$$

Since we are interested in fast switching of the diode, we choose $\alpha > 1$. In this case the inverse Laplace transform of Eq. (10) is [14]:

$$j_1(t) = \Delta n\frac{2}{\sqrt{\pi}}\left(\int_0^{\sqrt{t}} e^{-y^2}\,dy + e^{-\alpha t}\sqrt{\alpha-1}\int_0^{\sqrt{(\alpha-1)t}} e^{y^2}\,dy\right). \tag{11}$$

Since our calculations relate to the deviation of the concentration and current from their initial values, the total current in the system is

$$j_{tot}(t) = n_0 - j_1(t). \tag{12}$$

The dependence of the total current on time for various α is depicted in Fig. 1. We have chosen $n_0 = 1$ and $\Delta n = 0.9$. We can see that a pulse of reverse current arises at the beginning of the transient process with $\alpha \gg 1$. This pulse is responsible for the fast removal of excess carriers. But for $\alpha = 2$ and $\alpha = 0.5$, the negative pulse does not appear because the removal of excess carriers occurs mainly due to recombination. As it can be seen from Eq. (11) and Eq. (12), the final value of the current at $t \to \infty$ is equal to $n_0 - \Delta n$.

Now we consider a situation when the current flowing through the junction is controlled externally so that $j_{tot}(t) = n_0 - \Delta n(1 - e^{-\alpha t})$. Since $j \propto \partial n/\partial x$, by taking the partial derivative of Eq. (6) over ∂x, we obtain exactly the same equation for the current with the same initial and boundary conditions. Then the Laplace transform of the current is

$$j_p(x) = \Delta n e^{-x\sqrt{p+1}}\left[\frac{1}{p} - \frac{1}{p+\alpha}\right], \tag{13}$$

and the Laplace transform of the concentration at the junction is

$$n_p(x=0) = \int j_p(x)\,dx\,|_{x=0} = -\frac{\Delta n}{\sqrt{p+1}}\left[\frac{1}{p} - \frac{1}{p+\alpha}\right]. \tag{14}$$

Taking the inverse Laplace transform of Eq. (14), we have for $\alpha > 1$:

$$n_1(t) = \Delta n\frac{2}{\sqrt{\pi}}\left(\int_0^{\sqrt{t}} e^{-y^2}\,dy - \frac{e^{-\alpha t}}{\sqrt{\alpha-1}}\int_0^{\sqrt{(\alpha-1)t}} e^{y^2}\,dy\right), \tag{15}$$

and the total concentration is

$$n(x=0,t) = n_0 - n_1(t). \tag{16}$$

We can see from Eq. (15), the contribution of the second term, which is proportional to $1/\sqrt{\alpha-1}$, vanishes as α increases. Therefore, even if the current is switched very rapidly, the concentration of injected carriers still decays slowly according to the recombination law.

Obviously, the solutions we have obtained are valid for the process of switching the device on (we just have to change the sign of Δn). If we provide a step-like increase of the voltage across the junction, it will cause a large pulse of forward current whose magnitude is larger than the current in the ON-state, I_{ON}. This current would introduce the excessive carriers for a smaller time than that of the current-control switching.

Of course, this simple model just gives us a qualitative picture of the fast carrier removal and fails to produce real values of switching time. The major reason for this is our complete neglecting of the drift effects that could change the picture drastically. The exact description of these processes with the use of direct numerical simulations is presented below.

For our numerical simulations we have chosen the

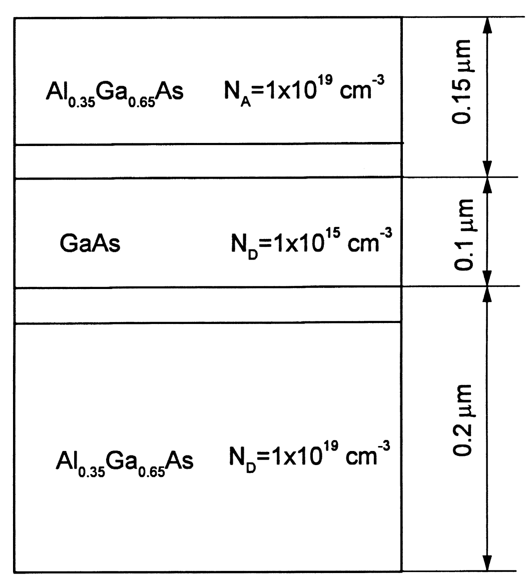

Fig. 2. A sketch of the model LED.

structure depicted in Fig. 2. The device consists of wide-bandgap heavily-doped AlGaAs p^+- and n^+-emitters that provide high injection efficiency of their majority carriers and a narrow-bandgap lightly-doped GaAs active region (the well) where the injected carriers are confined and recombine, and where light emits from. We have chosen graded heterojunctions at the boundaries of the active region (indicated by two lines parallel to the well in Fig. 2. Such a design is favorable because it makes the carrier capture to and escape from the active region easier and allows us to avoid the effect of thermionic emission that is typical for abrupt heterojunctions [15]. The thermionic emission current could restrict carrier escape from the well and, consequently, the reverse current arising during the process of fast switching. Another advantage of the design is that the graded heterojunctions allow one to diminish the parasitic surface recombination on the heterointerfaces [16] and to increase the quantum efficiency. We have chosen the width of the transient layers at the heterojunctions equal to 0.04 μm each, which is sufficient to consider them smooth and to make the drift-diffusion approach we have used for our numerical calculations valid.

We consider two forward-biased states of the LED. The first one corresponds to the ON-state with the current density of $I_{ON} = 10^4$ A/cm^2 and the forward voltage of $V_{ON} = 1.55$ V, the second one — to the OFF-state with the current density of $I_{OFF} = 10^2$ A/cm^2 and the voltage of $V_{OFF} = 1.34$ V. The value of I_{ON} is a typical threshold current in GaAs heterojunction lasers [17] and corresponds to the carrier concentration in the well of about 1.5×10^{18} cm^{-3}. The second state is a typical OFF state in which no light is being emitted from the well.

First, we consider switching the LED off. The process has been simulated as follows: the voltage across the device is ramped from V_{ON} to V_{OFF} for 10^{-11} s and then kept equal to V_{OFF}. In Fig. 3, we present the distributions of radiative recombination rate in the

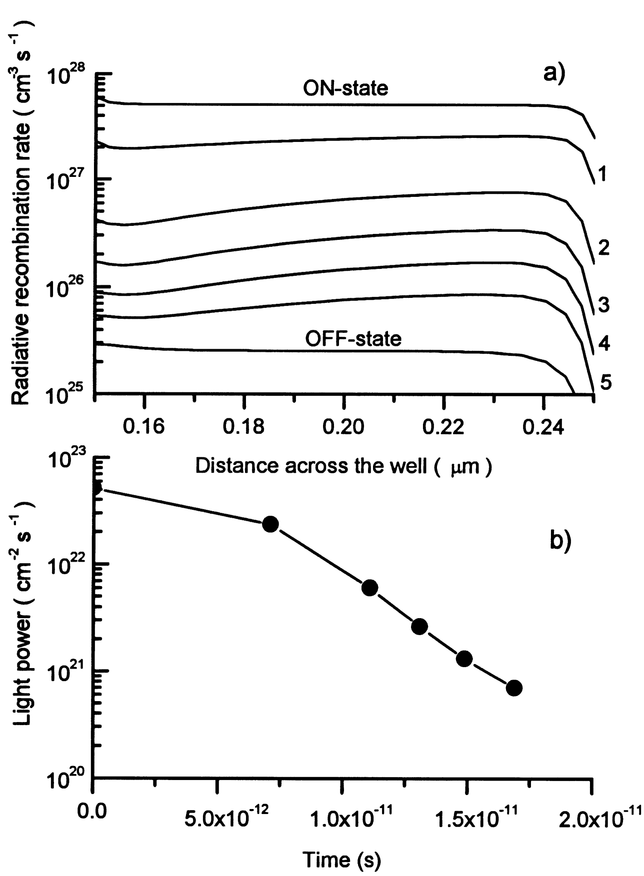

Fig. 3. Radiative recombination rate in the well vs the distance, counted from the top of the device shown in Fig. 1, during the process of switching the diode OFF at different time instants for $R_0 = 0$. t = 0 (ON-state), $t = 7.1 \times 10^{-12}$ s (1), $t = 1.11 \times 10^{-11}$ s (2), $t = 1.31 \times 10^{-11}$ s (3), $t = 1.49 \times 10^{-11}$ s (4), $t = 1.69 \times 10^{-11}$ s (5). (b) Time dependence of the total optical power emitted from the well.

well at various time instants during the switching process and the total optical power (the photon flux density) $P(t)$ that is emitted from the well given by

$$P(t) = \int_W C_{\mathrm{opt}}(x, t)\,\mathrm{d}x, \tag{17}$$

where the integration goes over the length of the active region $W = 0.1$ μm. The value of resistance R_0 connected in series with the LED is equal to zero.

As we can see, the characteristic time of the switching process is of the order of 10^{-11} s, while the radiative recombination time in the ON-state is $\tau_r = 2 \times 10^{-9}$ s. Naturally, the process causes a huge pulse of reverse current of about 5.5×10^5 A/cm^2 (see Fig. 4(b)) that removes the excessive carriers from the well. To ensure this fast removal, a large pulsed electric field of about 6×10^3 V/cm arises in the p$^+$-emitter, as it is seen in Fig. 4(a). Since the value of electron mobility in AlGaAs is much greater than that of hole mobility, the electric field in then n^+-emitter is much smaller. However, the pulsed current in both emitters is caused by majority carriers as it is seen from Fig. 4(b). Meanwhile, the pulsed current in the well is purely diffusive (see Fig. 3(a)).At the beginning of the switching process when the concentration of injected carriers in the well is still large, the slope in their distribution is noticeably smaller than that at $t = 1.11 \times 10^{-11}$ s at which the concentration has already dropped but the value of $\partial n/\partial x$ still should be large.

So we can conclude that it is the resistance of the p^+-emitter that restricts the value of reverse current if the external series resistance $R_0 = 0$. Therefore, the fast switching becomes possible only if the length of the p^+-region is small enough to allow the appearance of a large pulsed electric field in it. At the same time, a decrease in its length beyond 0.2 μm is meaningless due to the saturation of the hole velocity. Our calculations have shown that the optimal length is about 0.2–0.6 μm.

To find out how the series resistance influences the process of switching the LED off, we have performed numerical simulations for various values of R_0. For non-zero series resistances, the values of I_{ON} and I_{OFF} were kept the same, the forward voltage drops across

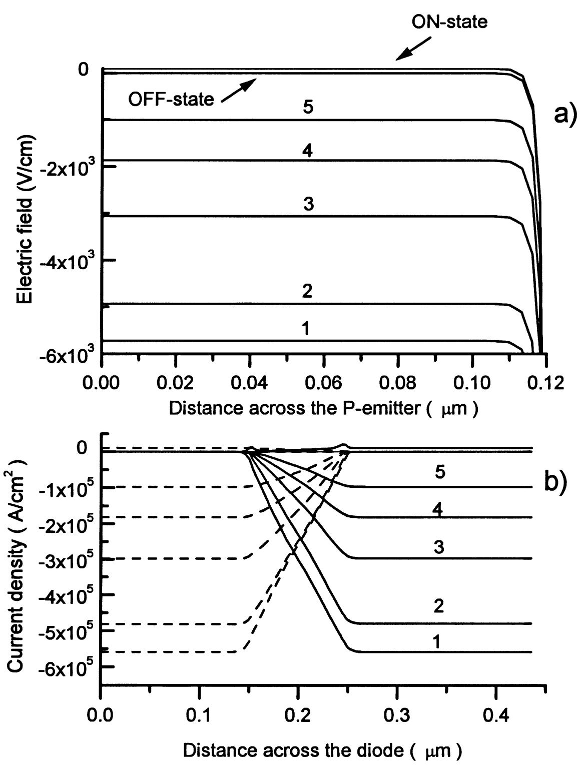

Fig. 4. (a) Electric field in the p^+-emitter vs the distance, counted from the top of the device shown in Fig. 2, during the process of switching the diode OFF at different time instants for $R_0 = 0$. $t = 0$ (ON-state), $t = 7.1 \times 10^{-12}$ s (1), $t = 1.11 \times 10^{-11}$ s (2), $t = 1.31 \times 10^{-11}$ s (3), $t = 1.49 \times 10^{-11}$ s (4), $t = 1.69 \times 10^{-11}$ s (5). (b) Electron (solid line) and hole (dashed line) current densities in the whole device vs distance at the same time instants.

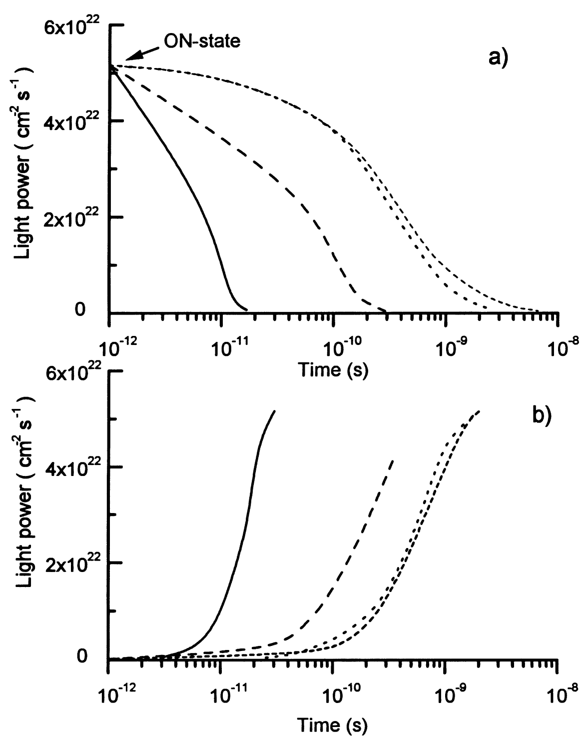

Fig. 5. Total optical power emitted from the well vs time during switching the diode OFF (a) and ON (b) at different series resistances: $R_0 = 0$ (solid line), $R_0 = 5 \times 10^{-6}$ Ω cm^2. (dashed line), $R_0 = 1.5 \times 10^{-4}$ Ω cm^2 (dotted line), and $R_0 = \infty$ (short-dashed line).

the whole system (LED plus resistor) being recalculated and eventually ramped between their new values. The case $R_0 = \infty$ actually corresponds to current-control switching. Here the current has been ramped between I_{ON} and I_{OFF} according to the same law as before.

In order to demonstrate the effect of the series resistance on the LED's switching speed, we have depicted time dependences of the total optical power emitted from the well while switching off the device (Fig. 5(a)) and on (Fig. 5(b)) at different series resistances. It is clearly seen that the voltage-control regime of switching ($R_0 = 0$) exhibits an approximately two-order-of-magnitude gain in speed of operation compared to the traditional current-control regime ($R_0 = \infty$).

Thus, we have shown both analytically and numerically that the speed of conventional current-control methods of switching of light-emitting diodes is limited by recombination processes in the active region. The characteristic time of these processes is of the order of several nanoseconds. We have also shown that there exists a possibility to increase the speed of operation considerably by controlling the voltage across the device rather than the current through it. A step-like change in the forward voltage results in a large pulsed current that rapidly removes excessive carriers from the active region if the device is being switched off and injects them into the active region if the device is being switched on. The characteristic time of these processes has been shown to be approximately two orders of magnitude smaller than the recombination time.

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