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On the Possibility of a Significant Increase in Semiconductors Photosensitivity Spatial Profiling Flux of Radiation

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1. Abstract

Theory-based, three new unknown photoelectric effects can be occurred in semiconductors under inhomogeneous optical illumination with specific profile shapes along electric field in semiconductor: self-amplification, self-quenching and sign self-inversion of photogeneration rate of mobile charge carriers. The general shapes of corresponding illumination profiles are calculated. The occurring effects cause by local photoexcited space charge (PSC). It is shown that profile shapes depend on parameters of semiconductor, dark electric field strength and temperature. Also, we determine general shapes of "neutral" profiles when local PSC although exists but does not affect the result of interaction of optical radiation with a semiconductor. In other words, calculations with such "neutral" profiles lead to the same result as with using quasi-neutrality approximation, which does not account PSC. The shape of "neutral" profile depends only on dark electric field strength, temperature and sample size along the electric field. Embodiments for all types of profiles are given. The results can be used in practice, first, to increasing significantly photoelectric response of semiconductor detectors of optical radiation.

2. Keywords: Semiconductors; Nonuniform band-to-band photogeneration of charge carriers; Electric field; Recombination center; Energy level; Photoinduced space-charge; Illumination profile; Self-Amplification; Self-Quenching and sign Self-Inversion of photogeneration rate of mobile charge carriers

3. Introduction

In my article (September 2019), it was theory-based that spatial inhomogeneous (exponential) density of photogeneration rate along the dark electric field in photoconductor can radically affect the magnitude of the photocurrent [1]. The effect is due to local PSC. Based on this result, the goal is to find out possible effects of spatial inhomogeneity of the incident optical radiation flux along the dark electric field on photoelectric response in semiconductors. In principle, such inhomogeneity with different profile shapes can be created in classic configuration when optical radiation flux falls perpendicular to electric field direction in semiconductor sample. The set-up of the problem is like specified in work [1]. We consider nondegenerate semiconductor with band-to-band photogeneration of excess charge carriers and prevail trap-assisted recombination. It is assumed that photoelectric effect is aimed to detect weak optical radiation [2,3].

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The latter statement allows to limit the consideration to linear approximation in g - the density of photogeneration rate of mobile charge carriers. One-dimensional case is analyzed when all parameters can change only along x axis. It is assumed that semiconductor is doped with shallow-level fully ionized donor atoms with concentrationN_D, and recombination of nonequilibrium charge carriers occurs through trap-levels of acceptor atoms with concentration$N$. It is assumed that acceptor atoms can be in either neutral or negatively singly charged states [4,5]. In other words, acceptor atoms create single recombination trap-level with energyE_t. Denote the concentration of charged acceptors asN_-. Then the concentration of neutral acceptors is:

$$N_0 = N - N_-. \qquad (1)$$

No illumination (dark) electric field strength E_0 is assumed to be uniform and directed along x axis, i.e., $E_0(x) = consnt \geq 0$. An important point is that the local quasi-neutrality of the sample under nonequilibrium conditions is not assumed.

4. Parametric technique to calculating dependence of concentration of equilibrium charge carriers on concentration of acceptor impurity

To calculate the dependence of equilibrium electron n_e and hole p_e concentrations on N we need to solve the neutrality equation:

$$n_e + N_-^e = p_e + N_D \qquad (2)$$

whereN_-^e is equilibrium concentration of charged acceptors.

Let's introduce parameter:

$$\delta = N_-^e / N_0^e, \qquad (3)$$

whereN_0^e is equilibrium concentration of neutral acceptor atoms.

Taking account that filling function of acceptor trap-levels is: [6,7].

$$f_A = \frac{1}{1+(1/2)\times exp[(E_t - E_F)/(k_B T)]} \quad (4)$$

wherek_B is Boltzmann constant and T is temperature.

From relations (1)-(4), expressing Fermi level energy E_F in terms of parameter δ we can obtain: [7,8].

$$n_e = \frac{\delta}{2} \times n_{tr} = \frac{\delta}{2} \times \frac{n_{tr}}{n_i} \times n_i \qquad (5)$$

$$p_e = \frac{2}{\delta} \times p_{tr} = \frac{2}{\delta} \times \frac{n_i}{n_{tr}} \times n_{ir} \qquad (6)$$

$$N = n_{tr} \times \frac{1+\delta}{2\times\delta^2} \times f(\delta) = \frac{n_{tr}}{n_i} \times n_i \times \frac{1+\delta}{2\times\delta^2} \times f(\delta) \qquad (7)$$

$$f(\delta) = B + A \times \delta - \delta^2 \qquad (8)$$

$$A = 2 \times \frac{N_D}{n_{tr}} = 2 \times \frac{N_D}{n_i} \times \frac{n_i}{n_{tr}} \quad B = 4 \times \frac{p_{tr}}{n_{tr}} = \left(\frac{2\times n_i}{n_{tr}}\right)^2 \qquad (9)$$

Here n_{tr} and $p_{tr}$are equilibrium electron and hole concentrations when Fermi level energy E_F coincides with energy of recombination trap-levelE_t, n_i is intrinsic concentration of charge carriers.

Maximum value of δ is found from solution of equation $f(\delta) = 0$ and is defined by the expression:

$$\delta_{max} = \frac{A}{2} + \sqrt{\frac{A^2}{4} + B} \qquad (10)$$

Expressions (5)-(10) define in parametric form dependences of equilibrium electron n_e and hole p_e concentrations on acceptor concentration$N$.

5. Parametric technique to calculating electron and hole lifetimes on concentration of acceptor impurity

In stationary case, charge state of recombination impurity atoms is determined by the equation:

$$R_n = R_p \qquad (11)$$

where electron R_n and hole $R_p$generation-recombination rates due to capture of charge carriers by trap-levels formed by acceptor impurity and thermal excitation from trap-levels to allowed bands are equal.

$$R_n = (n \times N_0 - \delta^{-1} \times n_e \times N_-) \times w_n, \quad R_p = (p \times N_- - \delta \times p_e \times N_0) \times w_p \quad (12)$$

Here n and p are electron and hole concentrations, w_n and w_p are capture probabilities of electron and hole to proper trap.

Small deflection linearization is done for relations (11) and (12) when $\Delta n = n - n_e$, $\Delta p = p - p_e$ and $\Delta N_0 = N_0 - N_0^e = -\Delta N_- = N_-^e - N_-$ are small. Then, by accounting of Poisson equation:

$$\Delta\rho \equiv \frac{\varepsilon}{4\pi} \times \frac{\partial \Delta E}{\partial x} = q \times (\Delta p - \Delta n - \Delta N_-) \quad (13)$$

we obtain: [8,9].

$$R_n = \frac{\Delta n}{\tau_n} + a_n \times div\Delta E \qquad (14)$$

$$R_p = \frac{\Delta p}{\tau_p} - a_p \times div\Delta E \qquad (15)$$

$$\Delta p = \frac{\tau_p}{\tau_n} \times \Delta n + (a_n + a_p) \times \frac{d\Delta E}{dx} \qquad (16)$$

$$\frac{1}{\tau_n} = w_n \times N \times \frac{\delta\times\theta}{1+\delta} \times \frac{N+(1+\delta)\times(1+\delta^{-1})\times(n_e+p_e)}{\delta\times\theta\times N+(1+\delta)\times(1+\delta^{-1})\times(n_e+\delta\theta p_e)}$$

(17)

$$\frac{1}{\tau_p} = w_p \times N \times \frac{\delta}{1+\delta} \times \frac{\delta\times N+(1+\delta)^2\times(n_e+p_e)}{\delta\times N+(1+\delta^2)\times(n_e+\delta\times\theta\times p_e)} \qquad (18)$$

$$a_n = \frac{\varepsilon}{4\times\pi\times q} \times \frac{(1+\delta)\times w_p\times N\times n_e}{\delta\times\theta\times N+(1+\delta)\times(1+\delta^{-1})\times(n_e+\delta\times\theta\times p_e)} \qquad (19)$$

$$a_p = \frac{\varepsilon}{4\times\pi\times q} \times \frac{(1+\delta)\times w_p\times N\times p_e}{N+(1+\delta)\times(1+\delta^{-1})\times(n_e+\delta\times\theta\times p_e)}.$$

(20)

Here ε - dielectric permittivity; $\Delta\rho$ - local nonequilibrium space charge; $\Delta E = E - E_0$ - change in electric field due to deflection of concentrations of electrons, holes and traps from equilibrium values; q - absolute value of electron charge; $\theta = w_p/w_n$. The first terms in expressions (14) and (15) mean the recombination rates of nonequilibrium electrons and holes (therefore, τ_n and $\tau_p$are proper lifetimes) under conditions of local quasi-neutrality relative to electric field ΔE, i.e., for sufficiently small values $|div\Delta E|$. We keep this terminology for τ_n and τ_p also in case of violation of quasi-neutrality, so that the values of τ_n and τ_p do not depend on value $div\Delta E$. Relations (5)-(10), (17) and (18) define parametrized dependences of τ_n and τ_p on$N$. This method of calculating dependences $\tau_n(N)$ and $\tau_p(N)$ allowed to predict the possibility of growth, including the giant splash, of charge carriers lifetimes with increasing in N [8,9]. Splash growth of $\tau_n(N)$ and $\tau_p(N)$ dependences with increasing in N is the main reason for the giant splash (up to several orders of magnitude) of photoelectric gain with increasing in N [10-13].

6. Non-quasi-neutral equation for distribution of concentration of nonequilibrium charge carriers

Recall that a solution to the problem is called non-quasi-neutral when, in contrast to quasi-neutral approximation, $div\Delta E$ is not considered to be zero in Poisson equation (13). In the linear approximation in$g$, the changes in density of electron ΔI_n and hole ΔI_p currents and (electron and hole components of photocurrent densityI_{ph}) are determined by expressions:

$$\Delta I_n = q \times \mu_n \times (E_0 \times \Delta n + n_e \times \Delta E) + q \times D_n \times \frac{\partial \Delta n}{\partial x}, \qquad (21)$$

$$\Delta I_p = q \times \mu_p \times (E_0 \times \Delta p + p_e \times \Delta E) - q \times D_p \times \frac{\partial \Delta p}{\partial x}, \qquad (22)$$

whereμ_n, μ_p, D_n and D_p - electron and hole mobilities and diffusion constants.

Electron and hole components of photocurrent density:

$$I_{ph} = \Delta I_n + \Delta I_p \qquad (23)$$

should obey equations of continuity:

$$\frac{\partial \Delta I_n}{\partial x} = q \times (R_n - g) \qquad (24)$$

$$\frac{\partial \Delta I_p}{\partial x} = q \times (g - R_p) \qquad (25)$$

Besides:

$$\frac{\partial \Delta I_{ph}}{\partial x} = 0 \qquad (26)$$

Let's restrict consideration by interval of bias voltage applied across the sample

$$V = E_0 \times W \qquad (27)$$

when dependences of μ_n and μ_p on electric field E_0 can be neglected. Here, W is sample dimension along electric field.

Equation for distribution of the concentration of nonequilibrium charge carriers (photocarriers) can be derivable from relations (11)-(26) without invoking local quasi-neutrality approximation [1, 11-13]. When illumination is inhomogeneous, i.e., when $g(x) \neq const$, this equation, e.g., for nonequilibrium electrons, is written as: [1, 13].

$$Q \times \frac{\partial^4 \Delta n}{\partial x^4} - D \times \frac{\partial^2 \Delta n}{\partial x^2} + \mu \times E_0 \times \frac{\partial \Delta n}{\partial x} + \frac{\Delta n}{\tau_n} = g_{ef}(x), \quad (28)$$

where

$$D = D_E + D_\xi + D_n^a,\ \mu = \mu_\xi + \mu_n^a, \quad (29)$$

$$D_E = \xi \times \tau_p \times \mu_p \times \mu_n \times {E_0}^2 \quad (30)$$

$$Q = \xi \times D_n \times {L_p}^2, \quad D_\xi = \xi_p \times \frac{\tau_p}{\tau_n} \times D_p + \xi_n \times D_n,$$

$$\mu_\xi = \xi_p \times \frac{\tau_p}{\tau_n} \times \mu_p - \xi_n \times \mu_n, \quad (31)$$

$$\xi = \frac{a_n + a_p}{\mu_n \times n_e + \mu_p \times p_e} = \frac{2 \times (a_n + a_p) \times \delta}{(\delta^2 \times \mu_n + B \times \mu_p) \times n_{tr}} \quad (32)$$

$$\xi_n = a_n / (\mu_n \times n_e + \mu_p \times p_e), \quad \xi_p = \xi - \xi_n = a_p / (\mu_n \times n_e + \mu_p \times p_e), \quad (33)$$

Ambipolar mobilities and diffusion constants equals to:

$$\mu_n^a = \frac{n_e \times \tau_p - p_e \times \tau_n}{(p_e + b \times n_e) \times \tau_n} \times \mu_n = \frac{\delta^2 \times \tau_p - B \times \tau_n}{(B + b \times \delta^2) \times \tau_n} \times \mu_n, \quad (34)$$

$$D_n^a = \frac{n_e \times \tau_p + p_e \times \tau_n}{(p_e + b \times n_e) \times \tau_n} \times D_n = \frac{\delta^2 \times \tau_p + B \times \tau_n}{(B + b \times \delta^2) \times \tau_n} \times D_n \quad (35)$$

$L_p = \sqrt{D_p \tau_p}$ - hole diffusion length. Right side of Eq. (28) is due to absorption of optical radiation and defined by expression:

$$g_{ef}(x) = g(x) + \xi \times \tau_p \times \left(\mu_p \times E_0 \times \frac{\partial g}{\partial x} - D_p \times \frac{\partial^2 g}{\partial x^2}\right). \quad (36)$$

The degree of deviation of nonequilibrium electron-hole plasma of the semiconductor from local quasi-neutrality is characterized by three dimensionless parameters ξ_n, ξ_p and $\xi = \xi_n + \xi_p$. By the way, in approximation of local quasi-neutrality $\xi_n = \xi_p = \xi = 0$.

7. New ideas

As can be seen from Eq. (28), the result of direct interaction of optical radiation with a semiconductor is described by Eq. (36), which depends not only on the density of the photogeneration rate of charge carriers $g(x)$, but also on its first and second derivatives. Illumination of semiconductor sample with inhomogeneous profile of intensity along external electric field, when $g(x) \neq consnt$, can affect significantly the magnitude of the photocurrent, as was early shown theoretically in work [1].

Based on this result, let's analyze principle possibilities that can be realized due to spatial inhomogeneity of the incident optical radiation along external electric field. For this purpose, in accordance with Eq. (36), we consider the equation:

$$A_{ef} \times \frac{\partial^2 g}{\partial x^2} - B_{ef} \times \frac{\partial g}{\partial x} + \zeta \times g(x) = 0 \quad (37)$$

where

$$A_{ef} = \xi \times D_p \times \tau_p$$

$$B_{ef} = \xi \times \tau_p \times \mu_p \times E_0 \quad (38)$$

If $g(x)$ is measured by values of g_0, where $g_0 = g_0(x) = const$ is density of a certain uniform photogeneration rate of charge carriers, then general dimensionless solution of equation (37) will be as follows:

$$g(x) = C_1 \times exp(a_1 \times x) + C_2 \times exp(a_2 \times x) \quad (39)$$

where

$$a_{1,2} = (1 \pm \sqrt{1 - 4\zeta \times r}) / (2 \times d) \quad (40)$$

$$r = \frac{A_{ef}}{{B_{ef}}^2} = \frac{k \times T}{\xi \times q \times \tau_p \times \mu_p \times {E_0}^2} \quad (41)$$

$$d = A_{ef} / B_{ef} = D_p / (\mu_p \times E_0) = kT / (q \times E_0) \quad (42)$$

The only restriction imposed on dimensionless integration constants C_1 and C_2 is that according to the physical meaning of density of photogeneration rate of mobile charge carriers $g(x) \geq 0$ always. As follows from Eqs. (34) - (39), dimensionless parameter ζ, depending on its sign and absolute value, has the following physical meaning.

7.1. Self-amplification of the density of photogeneration rate in $(1 + \zeta)$ times:

$$g_{ef}(x) = (1 + \zeta) \times g(x) > g(x) \quad (43)$$

This takes place if the profile $g(x)$ satisfies to Eq. (37) along with $\zeta > 0$.

7.2. Photogenerated charge does not affect the result of the interaction of optical radiation with a semiconductor:

$$g_{ef}(x) = g(x) \quad (44)$$

This is ensured by the profile of $g(x)$ satisfying Eq. (37) when $\zeta = 0$. Let's call such a profile as neutral, note here, local quasineutrality approximation gives the same result.

7.3. Self-quenching of the density of

photogeneration rate when:

$$0 < g_{ef}(x) = (1 + \zeta) \times g(x) < g(x) \qquad (45)$$

This will take place if the profile $g(x)$ satisfies Eq. (37) along with $-1 < \zeta < 0$.

7.4. Full self-quenching of photogeneration:

$g_{ef}(x) = 0$. This will take place if the profile $g(x)$ satisfies Eq. (37) along with $\zeta = -1$

In this case, despite the photogeneration of charge carriers, the incident radiation does not affect electrical resistance of semiconductor sample.

7.5. Sign self-inversion of the density of photogeneration rate:

$$g_{ef}(x) = (1 + \zeta) \times g(x) < 0 \qquad (46)$$

This will take place if the profile $g(x)$ satisfies Eq. (37) along with $\zeta < -1$.

In this case, despite the photogeneration of charge carriers, the incident radiation results in an increase in electrical resistance of semiconductor sample. Let's call this case as negative photoconductivity, since exposure to illumination with such profile reduces current. Here are some examples of $g(x)$ profiles for the family C_1=C_2 (Figure: 1-3). When plotting the graphs to compare of different profiles correctly, it was naturally considered that the total photogeneration rate of mobile charge carriers in the sample, regardless of profile shape and type of effect, should be the same, i.e.:

$$g_{tot} = \int_0^W g(x)dx = const \qquad (47)$$

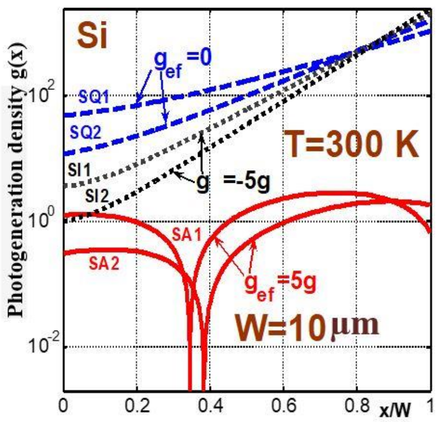

Figure 1: Density of photogeneration rate $g(x)$ profiles from family C_1=C_2 for self-amplification - curves **SA**, self-quenching - curves **SQ** and sign self-inversion - curves **SI** at two values of dark electric field strength E_0 (1 -E_0 = 30 V/cm, 2 - E_0 = 60V/cm). It is accepted: $N = N_D = 10^{15}$cm^{-3}, $n_i/n_{tr} = 10^4$. Values of $g(x)$ is measured in units of $g(0)$, in the case of sign self-inversion of $g(x)$ at $E_0 = 60$V/cm.

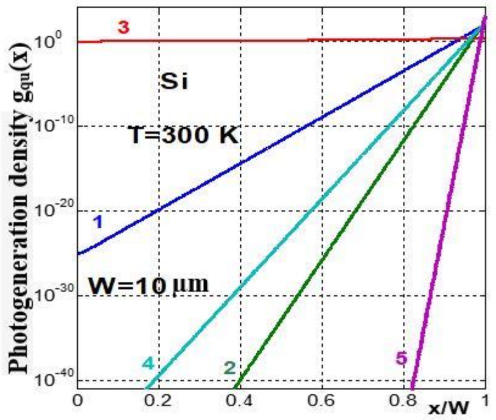

Figure 2: Effect of concentration of recombination impurity N on illumination profile from family C_1=C_2 for the case of self-quenching [$g(x) = g_{qu}(x)$]. It is accepted: $N_D = 10^{15}$cm^{-3}, $n_i/n_{tr} = 10^4$, $E_0 = 10$V/cm. Values N/N_D: **1** - 0.25; **2** - 0.5; **3** - 1; **4** – 2, **5** - 4. Values of $g_{qu}(x)$ is measured in units of $g_{qu}(0)$ in the case 3.

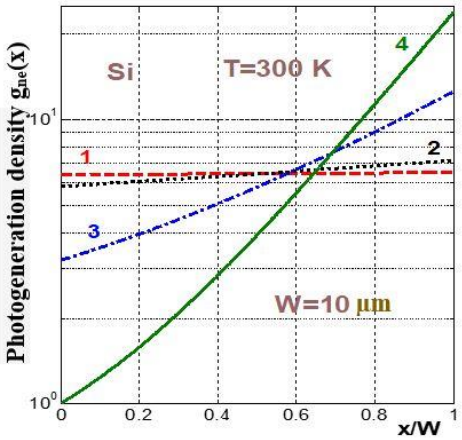

Figure 3: Effect of dark electric field strength E_0 on neutral profile of photogeneration rate $g(x) = g_{ne}(x)$. Values E_0, V/cm: **1** - 1, **2**-10, **3**-50, **4**–100. Values of $g_{ne}(x)$ is measured in units of $g_{ne}(0)$ in the case **4**.

8. Conclusion

Spatial inhomogeneity of illumination along the direction of dark electric field (axis x) can dramatically affect the photocurrent in semiconductors, as it was earlier clarified by the example of interband photogeneration of mobile charge carriers and subsequent trap-assisted recombination of those [1]. This article shows that such inhomogeneity can even lead to abnormal photoelectric effects. Depending on profile shape of the density of photogeneration rate $g(x)$ of charge carriers, phenomena of self-amplification, self-quenching, and sign self-inversion can occur. In the latter case, under exposure of illumination, the current through semiconductor sample decreases (negative photoconductivity). The corresponding photogeneration profiles are calculated. Profiles are defined by parameters of semiconductor material, temperature of the sample and magnitude of dark electric field strength (field in the absence of illumination exposure). The effects are due to a local photoexcited charge. Evidently, photoexcited local charge affects strength of photoexcited electric field $\Delta E(x) = E - E_0$. Moreover, as can be seen from Eqs. (13) - (15), such a charge affects the recombination-generation process. Therefore, photoelectric effects considered above are caused by change in the population (which is nonequilibrium) of recombination level. A similar change of nonequilibrium population occurs with increase in concentration of recombination centers N leading to a giant splash in lifetimes of mobile charge carriers and transit-time field-depended photoelectric gain G [1, 8-13]. Neutral shape of illumination exposure profile has been calculated, i.e., when photogenerated charge exists although, but does not affect the result of the interaction of optical radiation with a semiconductor. Only when profile is of such shape, simple $g(x)$ will be presented in distribution equation for concentration of nonequilibrium charge carriers (28). The results can be used to increase significantly in photoelectric response of semiconductors. For example, further increase in giant splash in photoconductivity of a semiconductor is possible with increase in concentration of recombination centers N [10-13].

The effects presented in this work can also be expected at interband (conduction band – valence band) recombination of nonequilibrium mobile charge carriers.

In the future, we plan to perform a wide and detailed analysis of, as it can be expressed, profile photoelectric effects.

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9. References

1. Kholodnov VA. J. of Communication Technology and Electronics 2019; 64: 1038.
2. Lutz G. Semiconductor Radiation Detectors. Springer. New York. 2007.
3. Rogalski A. Infrared Detectors. 2011; 43:187-210.
4. Milns AG. Deep Impurities in Semiconductors (New York–London–Sydney–Toronto: John Wiley. 1973.
5. Sadao Adachi. Properties of Semiconductor Alloys: Group-IV, III–V and II–VI Semiconductors. John Wiley & Sons. 2009.
6. Blackmore JS. Semiconductor Statistics. 1962.
7. Blackmore JS. Solid State Physics. Cambridge University Press. 1985.
8. Drugova A, Kholodnov VA. Solid-St. Electronics. 1995: 38: 1247.
9. Kholodnov VA. Semiconductors, 1996; 30: 538.
10. Kholodnov VA. JETP Lett. 1998; 67: 685.
11. KholodnovVA. Proceedings of SPIE. 1999; 98: 3819.
12. Kholodnov VA, Drugova AA. Tech. Phys. Lett., 2002; 28: 714.
13. Kholodnov VA, Nikitin MS. In book: Optoelectronics - materials and devices, Ed. S. L. Pyshkin and J. Ballato 2015; 12:301-348.

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