

Charge neutrality in heavily doped emitters

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The applicability of the quasineutrality approximation to modern emitters of solar cells is analytically reviewed. It is shown that this approximation is fulfilled in more than 80% of the depth of a typical solar-cell emitter, being particularly excellent in the heavily doped regions beneath the surface where most of the heavy doping effects arise. Our conclusions are in conflict with Redfield's recent affirmations.

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Recently the application of the quasineutrality approximation to the heavily doped emitters commonly used in solar cells and transistors has been criticized by Redfield.¹⁻³ He affirms that the strong doping gradients of modern emitters give rise to nonuniform electrostatic fields important enough to invalidate the charge neutrality assumption. Therefore he concludes that conventional emitter models based on that approximation are wrong.

It is the purpose of this letter to check the quasineutrality approximation in a typical heavily doped emitter used in solar cells. For the interest of comparison we select here the same emitter used by Redfield in his work.¹ It consists on a *n*-type erfc-profile emitter, 0.25 μm thick and with a surface impurity concentration of 2.10²⁰ cm⁻³. None of the heavy doping effects or degeneracy effects are going to be included here since this is still a matter of intense investigation. These considerations will be investigated in a further study.

In equilibrium conditions the total electric current at every point within the emitter must be zero:

$$J_n = qD_n(dn/dx) - q\mu_n nE = 0. \quad (1)$$

To maintain diffusion currents equal but opposite to drift currents a nonuniform electric field is required:

$$E(x) = \frac{kT}{q} \frac{1}{n(x)} \frac{dn(x)}{dx}. \quad (2)$$

The quasineutrality approximation consists on assuming that there is not a significant difference between the majority carrier concentration *n*(*x*) and the net concentration of donor atoms in the emitter *N_d*(*x*) = *N_D*(*x*) - *N_A*(*x*). Mathematically this approximation is valid when the following inequality applies:

$$| [N_d(x) - n(x)] / N_d(x) | \ll 1. \quad (3)$$

Within this approximation the electric field is

$$E(x) = \frac{kT}{q} \frac{1}{N_d(x)} \frac{dN_d(x)}{dx}. \quad (4)$$

To check this assumption let us write Poisson's equation for a sufficiently extrinsic semiconductor to neglect any minority-carrier effects

$$dE(x)/dx = (q/\epsilon\epsilon_0) [N_d(x) - n(x)]. \quad (5)$$

With the aid of Eqs. (4) and (5), inequality (3) can be expressed as

$$L_D^2(x) \left| \frac{d}{dx} \left(\frac{1}{N_d(x)} \frac{dN_d(x)}{dx} \right) \right| \ll 1, \quad (6)$$

where *L_D* is the extrinsic Debye length

$$L_D(x) = [\epsilon\epsilon_0 kT / q^2 N_d(x)]^{1/2}. \quad (7)$$

In fact, what we do when combining Eqs. (3), (4), and (5) is first to calculate the electric field in the charge-neutrality condition. Then we check if the gradient of this field is important enough to significantly change the majority-carrier concentration from the net donor concentration. If this is so, inequality (3) is not fulfilled and the calculated electric field is wrong because our assumption is not valid. If inequality (3) applies the contribution of majority carriers to the electric field is negligible and quasineutrality applies.

Let us study Redfield's profile

$$N_d(x) = N_s \operatorname{erfc}(ax) - N_B, \quad (8)$$

where *N_s* = 2.10²⁰ cm⁻³, *N_B* = 5.10¹⁵ cm⁻³, and *a* = 1:19.10⁵ cm⁻¹ (corresponding to a junction depth of 0.25 μm)³.

With this profile inequality (6) is rewritten as

$$L_D^2(x) \frac{4a^2 N_s}{\sqrt{\pi}} \frac{e^{-(ax)^2}}{N_d^2(x)} \left| ax N_d(x) - \frac{N_s}{\sqrt{\pi}} e^{-(ax)^2} \right| \ll 1. \quad (9)$$

The left-hand side of inequality (9) has been calculated and is drawn under the symbol Δ on Fig. 1 as a function of

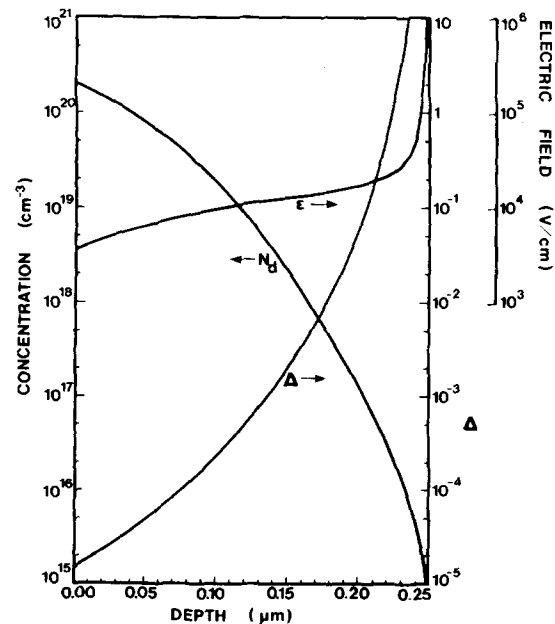


FIG. 1. Δ(Eq. 9), electric field and net donor impurity profile as a function of distance within the emitter.

emitter depth from the surface. It is seen that Δ is much less than 1 in the 83% of the emitter, being insignificantly small in the region adjacent to the surface. It is in fact in this heavily doped region right beneath the surface where most of the conflicting effects are supposed to occur: band-gap narrowing,⁴ Auger recombination,⁵ and Shockley–Read–Hall recombination.⁶

Also in Fig. 1 the emitter impurity profile (8) and the electric field calculated with (4) are shown. Note the slowly increasing field as we advance in depth.

Degeneracy effects would only severely affect our calculation in a region right next to the surface where impurity concentration is in the order of 10^{20} cm^{-3} . Redfield considered degeneracy in his work and he obtained a considerably flatter electric field near the surface than we do here. This implies that the quasineutrality approximation is even better when degeneracy is included.

As a conclusion we are able to assess that with classical

emitter models, which do not include any phenomena associated with heavy doping, most of the thickness of a shallow solar-cell emitter is under charge neutrality within a good approximation. Therefore the discussion concerning heavy doping effects occurring in emitters is still open.

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Preparation of amorphous silicon films by chemical vapor deposition from higher silanes $\text{Si}_n\text{H}_{2n+2}$ ($n > 1$)

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Amorphous silicon films have been prepared by chemical vapor deposition from higher silanes $\text{Si}_n\text{H}_{2n+2}$ ($n > 1$) in the temperature range 380–500 °C. The films show electrical properties comparable to those prepared by the plasma discharge of silanes. Gold Schottky devices were fabricated with internal short-circuit currents of 12 mA/cm² under AM1 illumination over an area of 2.0 cm².

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In recent years, substantial progress has been made in the development of efficient, thin-film photovoltaic devices based upon amorphous silicon (*a*-Si). Solar conversion efficiencies in the range of 5% have been achieved.¹ The breakthrough which precipitated this progress was the realization that alloying *a*-Si with hydrogen² resulted in a drastic reduction of the density of states in the *a*-Si energy gap. It was found that the electronic properties of *a*-Si:H could be controlled over a wide range by substitutional doping and that the photosensitivity of the films was dramatically better than that of the previous *a*-Si, presumably because of the elimination of photocarrier recombination centers.

Device quality *a*-Si:H films have been deposited by the plasma discharge³ of monosilane (SiH_4) or by the sputtering⁴ of silicon in a hydrogen atmosphere. *a*-Si may also be produced by the pyrolytic decomposition of SiH_4 .⁵ However, due to the high temperatures required to achieve appreciable

deposition rates (500–750 °C),⁵ bonded hydrogen in the resulting films is limited⁶ (1% compared to the 15–50% obtained by the plasma discharge methods). Consequently, the defect density and density of gap states for such films produced by chemical vapor deposition (CVD) from SiH_4 is orders of magnitude larger than for films obtained by plasma discharge methods. This makes CVD *a*-Si from SiH_4 unusable for photovoltaic device applications without post-deposition treatment.⁷ Recently, the deposition of highly photosensitive *a*-Si:H from the plasma discharge of disilane (Si_2H_6) has been reported.⁸

We propose an alternate CVD process for the formation of *a*-Si with appreciable hydrogen alloying, based on the pyrolytic decomposition of higher silanes. Monosilane is the first member of an homologous series of compounds ($\text{Si}_n\text{H}_{2n+2}$, $n = 1, 2, \dots$). Similarly to SiH_4 , the higher silanes decompose when heated to yield other silicon hydrides and hydrogen gas.⁹ Since the higher silanes decompose at lower temperatures than SiH_4 we wished to determine if it were possible to make *a*-Si films by CVD from higher silanes and

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