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# Figure of merit for front electrodes of solar cells

Nan Hu[a], Hongkun Cai[a,*], Xiaowan Dai[a], Guifeng Chen[b], Yong Wang[c], Dexian Zhang[a]

[a] Department of Electronic Science and Engineering, College of Electronic Information and Optical Engineering, Nankai University, Tianjin 300071, China
[b] School of Materials Science and Engineering, Hebei University of Technology,Tianjin 300130, China
[c] Haitai New Energy Technology Co. Ltd., Tangshan 064100, China

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ABSTRACT

Conventional figures of merit often characterize the optical and electrical properties of transparent conductive thin films and are widely applied in research and industry. However, an appropriative figure is necessary to evaluate the front electrodes of solar cells. So an appropriate figure of merit is therefore proposed in this paper, specifically designed for the evaluation of the front electrodes of solar cells. The proposed figure is adapted from $\Phi_{TC}$, the most commonly used conventional figure of merit, with two changes. First, external quantum efficiency functions for different types of solar cells are explicitly considered. Second, data from the air mass 1.5 spectrum are used as weight factors to calculate the mean optical transmittance. With these two changes, the proposed figure of merit is shown to be well adapted to the photovoltaic field. To validate it, silicon heterojunction solar cells with different front electrodes were simulated as examples. By comparing the simulation results and the respective values of the proposed figure, it is evident that this figure of merit provides values that are proportional to the conversion efficiencies of solar cells. The proposed figure can therefore be used in the selection and manufacturing of front electrodes of solar cells. In addition, two variations on this figure of merit are proposed, specifically adapted to the characteristics of multiple electron-hole pairs cells and thermophotovoltaic cells.

## 1. introduction

Transparent conductive thin films are widely applied in solar cells and panel displays. Both the optical transmittance and electrical conductivity of these films should be as large as possible. However, for most transparent conductive materials, these two properties conflict; i.e., if a transparent conductive coating has high optical transmittance, its electrical conductivity is typically low, and vice versa.

Several figures of merit have been introduced to evaluate the overall performance of transparent conductive films. Fraser et al. proposed a figure of merit for the first time [1]. They defined their figure of merit ($F_{TC}$) as

$$F_{TC} = T/R_{Sq} = \sigma t\exp(-\alpha t) \tag{1}$$

where $T$ is the mean value of the optical transmittance(the wavelength range from 450 nm to 550 nm is considered here), $R_{Sq}$ is the sheet resistance in Ω/square (Ω/□), $\alpha$ is the optical absorption coefficient measured in $\text{cm}^{-1}$, $t$ is the thin film thickness in cm and $\sigma$ is the electrical conductivity in $\Omega^{-1}$ $\text{cm}^{-1}$. Haacke [2] has also defined a related figure of merit ($\Phi_{TC}$):

$$\Phi_{TC} = \frac{T^{10}}{R_{Sq}} = \sigma t\exp(-10\alpha t) \tag{2}$$

which uses the tenth power of $T$ instead.

A different figure of merit (FOM) was defined by Fernándezet al. [3], as

$$FOM = -1/\rho_s\cdot\ln(T) = \sigma\alpha t \tag{3}$$

where $\rho_s$ is resistivity. The method of introducing$\sigma$, $\alpha$ and $t$ into the equation was first suggested by Haacke [2]. With this change, and fixing the value of $\sigma$ and $\alpha$, all the above three equations can be seen as functions of the film thickness $t$: $F_{TC}(t)$,$\Phi_{TC}(t)$, $FOM(t)$, and $T(t)$.

Fig. 1 shows plots of $F_{TC}(t)$, $\Phi_{TC}(t)$, $FOM(t)$, and $T(t)$. In this figure, $\sigma$ is set to $2\times10^3$ $\Omega^{-1}$ $\text{cm}^{-1}$, and $\alpha$ is set to$1.1\times10^4$ $\text{cm}^{-1}$. Both these values are in the normal range for indium tin oxide (ITO) films in the 450–550 nm waveband. Parameter $\alpha$ varies with wavelength $\lambda$; however, for simplicity, it was fixed at a specific value. Fig. 1 depicts some important characteristics of these functions.

As shown in Fig. 1(a), $F_{TC}(t)$ attains its maximum value when the value of $T(t)$ is as low as 37%. In contrast, the value of $T(t)$ is approximately 85–95% when $\Phi_{TC}(t)$ reaches its maximum value. A value ranging from 85–95% is a desirable value for the optical

* Corresponding author.
*E-mail address:* caihongkun@nankai.edu.cn (H. Cai).

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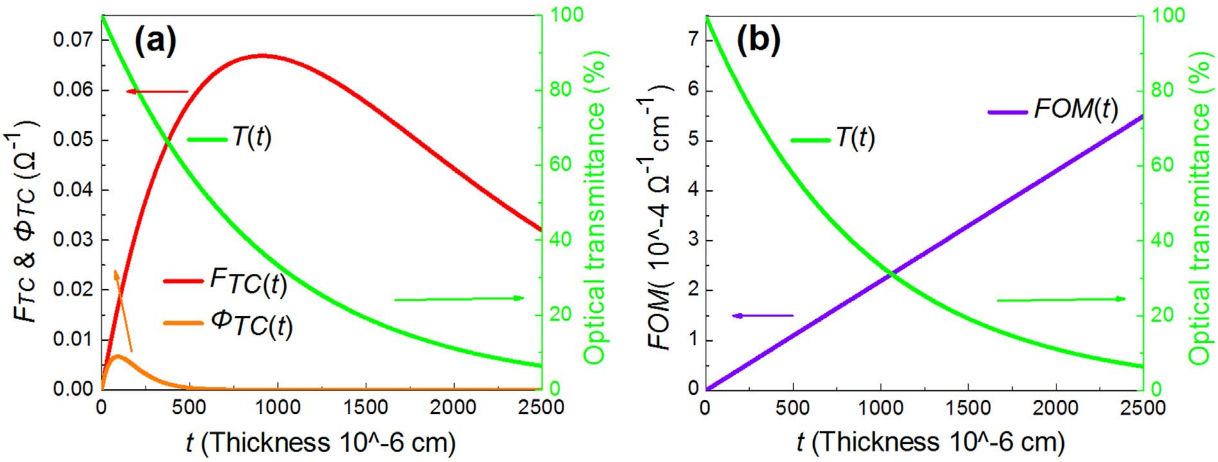


**Fig. 1.** Plots of $F_{TC}(t)$, $\Phi_{TC}(t)$, $FOM(t)$, and $T(t)$.(a) $F_{TC}(t)$,$\Phi_{TC}(t)$ versus $T(t)$ (b) $FOM(t)$ versus $T(t)$.

transmittance in any application. Owing to the use of the tenth power, $\Phi_{TC}$ can avoid the low optical transmittance when achieving its maximum value. Therefore, the tenth power of $T$ in $\Phi_{TC}$ is effective. The curve for $FOM(t)$ shows a monotonic increase with $t$, whereas $T(t)$ decreases monotonically with $t$. This means that a thick transparent-conductive-thin-film may have a high *FOM* value, even though its optical transmittance may be too low for any practical application. Thus, *FOM* does not fit for evaluating properties of front electrodes in the photovoltaic field.

To date, $\Phi_{TC}$ has been extensively applied. It has been used as an universal index for many types of transparent conductive thin films. However, the front electrodes of solar cells have their own characteristics, which differ from those in other fields. A figure of merit was therefore designed by us for only the front electrodes of solar cells based on $\Phi_{TC}$.

## 2. Discussion

### 2.1. Proposed figure of merit

The conventional figures can be used to represent the overall performance of transparent conductive thin films. Nevertheless, they should be improved in two regards aspects for evaluating the front electrodes of solar cells. First, they should take the spectral responsivity into account, which is fundamentally different of solar cells. Secondly, when testing solar cells, the air mass 1.5 (AM1.5) light source is typically used as a standard light source. Therefore, a weighted arithmetic mean should be used to obtain the transmittance values of the front electrodes, with the external quantum efficiency of the specific solar cell and the photon flux density of the AM1.5 spectrum being used as weight factors.

Based on the above considerations, a figure of merit, $F_H(k)$, was designed for the specific purpose of evaluating the properties of the front electrodes of solar cells

$$F_H(k) = \frac{(Q_A/Q_T)^{10}}{R_{Sq}} \tag{4}$$

The subscript $k$ in Eq. (4) indicates the specific type of solar cell. Because different types of solar cells have different *EQE* functions, $k$ is used to denote the solar cell type. This means that a certain transparent conductive thin film may have different $F_H(k)$ values if it is used as a front electrode on different solar cells. $Q_T$ is the total absorbable photon flux density in the AM1.5 spectrum. It denotes the total flux density of AM1.5 light that is absorbable by the solar cell. $Q_A$ is the total effective photon flux transmission density. It represents the flux that crosses the front electrode and will then energize carriers in the solar cell. $Q_A$and $Q_T$have the same domain of definition as the absorbable waveband of the specific solar cell. The photon flux density ratio $Q_A/Q_T$is therefore another form of optical transmittance, specifically adapted for photon density transmittance. The tenth power of $Q_A/Q_T$, the numerator of the proposed figure, is retained, to avoid the problem of having $F_H(k)$ peak at low optical transmittances, as discussed above for $\Phi_{TC}$. The denominator of $F_H(k)$, $R_{Sq}$, is the sheet resistance as in$\Phi_{TC}$. $Q_A$ can be calculated by

$$Q_A = \int_{300}^{\lambda_{Max}} P(\lambda)\cdot T(\lambda)\cdot EQE(\lambda)\mathrm{d}\lambda \tag{5}$$

where the lower integration limit of 300 nm corresponds to the lower wavelength limit in the AM1.5 spectrum, and $\lambda_{MAX}$ is the maximum absorbable wavelength of the solar cell. $P(\lambda)$ is the photon flux density function of the AM1.5 spectrum. $T(\lambda)$ is the optical transmittance function versus $\lambda$, which depends on the material and thickness of the front electrode. $EQE(\lambda)$ is the external quantum efficiency function, which is a fundamental difference between solar cells. In other words, $\lambda_{MAX}$ is the cutoff wavelength of $EQE(\lambda)$. Because of the joint effect of $T(\lambda)$ and $EQE(\lambda)$ in Eq. (5), $Q_A$ can be viewed as the quantity of photons that end up energizing carriers, per unit time and unit area. $Q_T$ is the total absorbable photon flux density in the AM1.5 spectrum by

$$Q_T = \int_{300}^{\lambda_{Max}} P(\lambda)\mathrm{d}\lambda \tag{6}$$

Two aspects should be noted in Eqs. (5) and (6). First, that photon flux density data are being used, because they can be applied to any solar cell field. Second, that integration is a theoretical continuous method; in reality, both the AM1.5 spectrum and the optical transmittance spectrum are discrete spectra, with 1–10 nm separation between adjacent values. Therefore, both $Q_A$and $Q_T$ should in practice be calculated by discrete sums, as in Eqs. (7) and (8). From these equations, it becomes evident that $Q_A/Q_T$is the weighted average of $T(\lambda)$, with the external quantum efficiency of the specific solar cell and the photon flux density of the AM1.5 spectrum being used as weight factors.

$$Q_A = \sum_{\lambda=300}^{\lambda_{MAX}} P(\lambda)\cdot T(\lambda)\cdot EQE(\lambda) \tag{7}$$

$$Q_T = \sum_{\lambda=300}^{\lambda_{MAX}} T(\lambda) \tag{8}$$

### 2.2. Calculation and simulation

To show the detailed calculation process, the $F_H$(SHJ) values of