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Thin layer ablation with lasers of different beam profiles - Energy efficiency and over filling factor

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Abstract

Structuring and patterning of thin layer via selective laser ablation is one of the key technologies in production of display and photovoltaic. Concurrently, there are two ablation processes used in production of thin film solar cells: Scribing via selective ablation and edge isolation via deletion. The common laser beams have circular cross section. Furthermore, the most currently lasers of high beam quality have Gaussian beam profile. Because of threshold behaviour Gaussian beam profile is not favourable for ablation process. On the other side there are emerging laser concepts which deliver rectangular or saqure top-hat beams with high beam quality. In this paper we will discuss the fundamentals of ablation processes with circular Gaussian beams, one dimensional top-hat beams and two dimensional square top-hat beams. The major issues will be the energy efficiency of the process and the area over filling aspect for the different beam profiles. The corresponding experimental results will be presented.

1 Introduction

Thin films plays increasingly important role in our modern society, in display and photovoltaic. The two major aspects of thin films are generation of thin film and the structuring or modifcation of thin film. Because of their spatial focusability and temporal controlability, laser beams are increasingly used for structuring and modifcation of thin film.

Concurrently, there are two ablation processes used in production of thin film solar: Scribing via selective ablation and edge isolation via deletion. To reduce the Ohm loss solar active layer is segmented in zones. The active zones are connected in series through homogeneous vapour deposition process and scribing process in turn. For electrical isolation and hermetic sealing of solar cells all layers in the boundary region of the completely processed solar cells on glass substrate have to be removed via deletion. Because of its huge application potential laser ablation process is also intensively investigated for scribing and structuring of thin films on Si-solar wafer /1, 2, 3/.

The common laser beams have circular cross section. Furthermore, the most currently lasers of high beam quality have Gaussian beam profile. Because of threshold behaviour Gaussian beam profile is not favourable for ablation process /1, 2, 3/. The emerging INNOSLAB laser concept delivers one dimensional line shaped top-hat beam with high beam quality /4, 5, 6, 7/. The one dimensional line shaped beam can be transformed to a circular Gaussian beam or to a two dimensional top-hat beam with square or rectangular cross section. In this paper we will discuss the fundamentals of ablation processes with circular Gaussian beams, one dimensional top-hat beams and two dimensional square top-hat beams. The major issues will be the energy efficiency of the process and the area over filling aspect for the different beam profiles.

2 Effective Energy Efficiency *EEE*

2.1 Circular Gaussian beam

Firstly, we consider a circular Gaussian beam with pulse energy of E. It is focused down to a spot with radius of a on the surface of workpiece. The fluence $\phi(r)$ of the circular Gaussian beam is given by

(1) $$\phi(r) = \frac{2E}{\pi a^2} e^{-2r^2/a^2} = \phi_0 e^{-2r^2/a^2}$$

where $\phi_0 = \frac{2E}{\pi a^2}$ is the maximum fluence on the axis.

Given the threshold fluence for the ablation process ϕ_{th} we have

(2) $$\phi_{th} = \phi(r_{th}) = \phi_0 e^{-2r_{th}^2/a^2}$$

and

(3) $$r_{th}^2 = \frac{a^2}{2} \ln(\frac{\phi_0}{\phi_{th}}) = \frac{a^2}{2} \ln \alpha$$

where r_{th} is the radius with the threshold fluence and $\alpha = \frac{\phi_0}{\phi_{th}}$ is the fluence ratio of the maximum fluence to the threshold fluence.

The energy inside the circle r_{th} is given by the integral of the fluence:

(4) $$\begin{aligned} E(r_{th}) &= \pi \int_0^{r_{th}} \phi(r) r dr \\ &= E(1 - \frac{1}{\alpha}) \end{aligned}$$

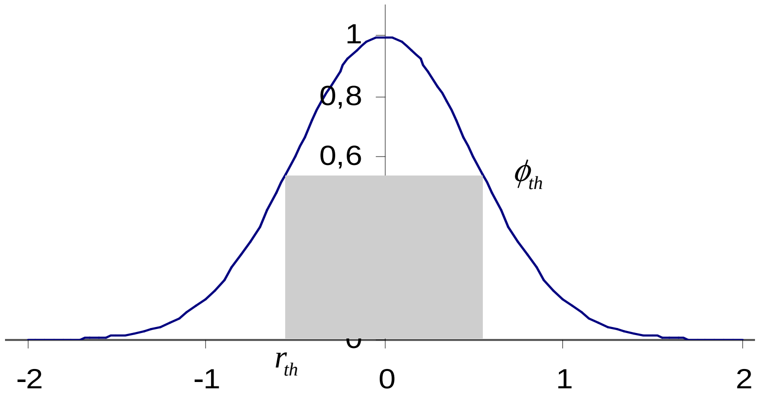

Fig.1: Fluence distribution of a Gaussian beam.

As shown in Fig. 1, the effective process energy useful for the ablation is the product of the disc area defined by r_{th} and the threshold fluence ϕ_{th}:

(5) $$E_{eff} = \pi r_{th}^2 \phi_{th} = \frac{E}{\alpha} \ln \alpha$$

For characterizing the efficiency of the ablation process we define the effective energy efficiency as the ratio of the effective process energy and the total energy. It is given by:

(6) $$EEE^{gaus} = \frac{E_{eff}}{E} = \frac{1}{\alpha} \ln \alpha$$

Fig. 2 shows the dependence of effective energy efficiency on the fluence ratio. Firstly, the effective energy efficiency increases with the fluence ratio. After a maximum it decreases with increasing fluence ratio.

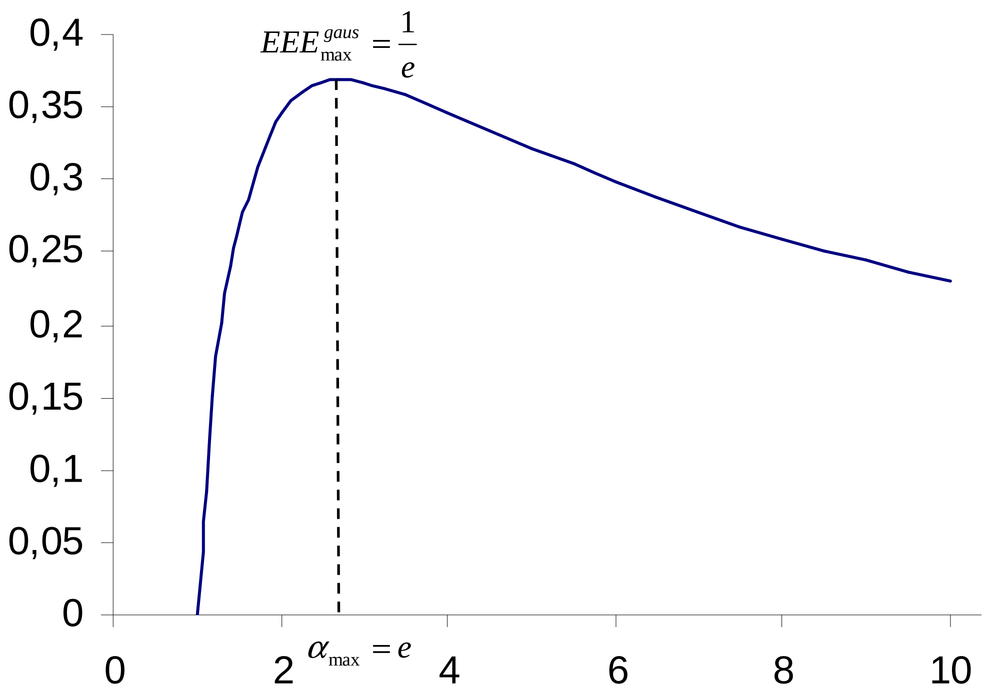

Fig. 2: Dependence of effective energy efficiency on the fluence ratio for a circular Gaussian beam.

There is a maximum value of the effective energy efficiency. It is determined by:

(7) $$EEE^{gaus\prime}(\alpha_{max}) = 0$$

The maximum of the effective energy efficiency is reached when the fluence ratio is given by:

(8) $$\alpha_{max} = e = 2.718$$

The corresponding maximum of the effective energy efficiency is equal to:

(9) $$EEE_{\max}^{gaus} = \frac{1}{e} = 0.368$$

That means that only 36.8% energy is maximumly useful for the ablation process. Other portion of the pulse energy is waste energy and does not contribute to the ablation process. Even worse, the waste energy will heat the substrate and lead to undesired effect and influence on the substrate.

In case of given threshold and pulse energy the optimal beam radius for obtaining maximum effective energy efficiency is determined by:

(10) $$a_{opt} = \sqrt{\frac{2E}{\pi e \phi_{th}}}$$

In case of given threshold and spot size ablated by each pulse the pulse energy required can be calculated by

(11) $$E = e \cdot \pi r_{spot}^2 \phi_{th}$$

2.2 1D top-hat beam

In the following we will discuss the ablation process with one dimensional Gaussian top-hat beam. For a one-dimensional Gaussian top-hat beam with pulse energy of E, the length of b and the width $2a$, the spatial distribution of the fluence is given by:

(12) $$\phi(x) = \frac{E}{ab}\sqrt{\frac{2}{\pi}} e^{-2x^2/a^2}$$

For threshold fluence I_{th} we have:

(13) $$\phi_{th} = \phi(x_{th}) = \frac{E}{ab}\sqrt{\frac{2}{\pi}} e^{-2x_{th}^2/a^2} = \phi_0 e^{-2x_{th}^2/a^2}$$

Where $\phi_0 = \frac{E}{ab}\sqrt{\frac{2}{\pi}}$ is the maximum fluence and the

(14) $$x_{th} = \frac{a}{\sqrt{2}}\sqrt{\ln(\frac{\phi_{th}}{\phi_0})} = \frac{a}{\sqrt{2}}\sqrt{\ln\alpha}$$

where $\alpha = \frac{\phi_0}{\phi_{th}}$ is the fluence ratio of the maximum fluence to the threshold fluence.

The energy within the width $2x_{th}$ is

(15) $$E(x_{th}) = 2b\int_0^{x_{th}} \phi(x)dx = Eerf(\frac{\sqrt{2}}{a} x_{th})$$

The effective effective energy is given by:

(16) $$E_{eff} = 2bx_{th}\phi_{th} = \frac{2}{\sqrt{\pi}}\frac{E}{\alpha}\sqrt{\ln\alpha}$$

The effective process efficiency is given by:

(17) $$EEE^{1d} = \frac{E_{eff}}{E} = \frac{2}{\sqrt{\pi}}\frac{1}{\alpha}\sqrt{\ln\alpha}$$

Fig. 3 shows the dependence of effective energy efficiency on the fluence ratio. The behavior is similar as by circular Gaussian beam. Firstly, the effective energy efficiency increases with the fluence ratio. After a maximum it decreases with increasing fluence ratio.

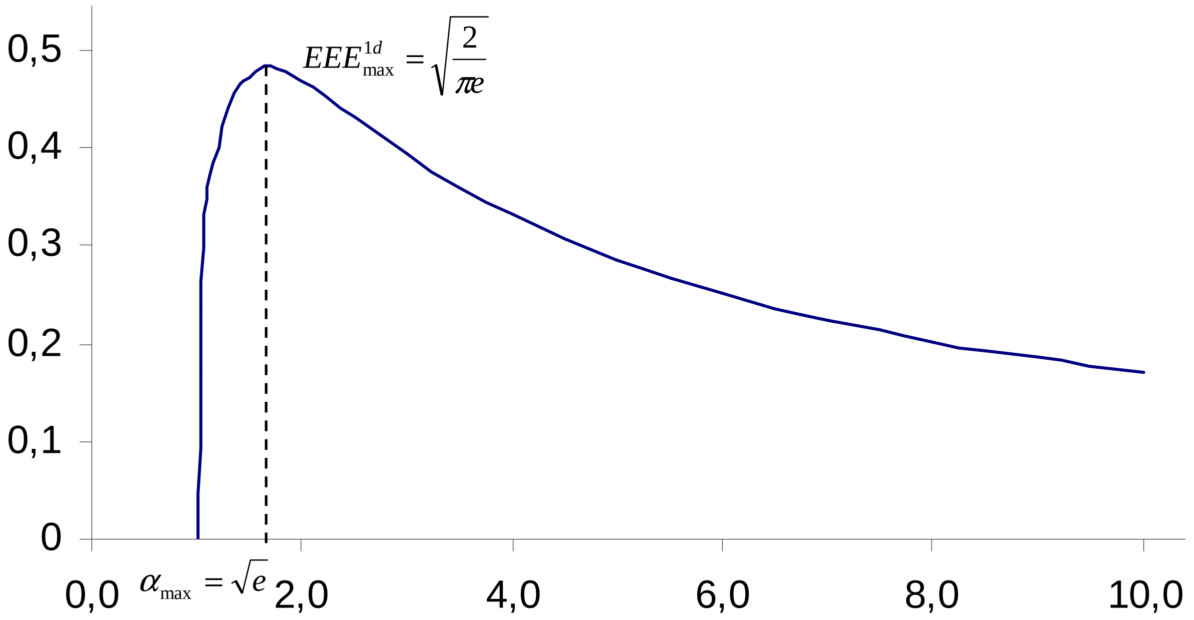

Fig. 3: Dependence of effective energy efficiency on the fluence ratio for a one dimensional top-hat beam.

The maximum of the effective energy efficiency is reached when the fluence ratio is given by:

(18) $$\alpha_{max} = \sqrt{e} = 1.648$$

The corresponding maximum of the effective energy efficiency is equal to:

(19) $$EEE^{1d}_{max} = \sqrt{\frac{2}{\pi e}} = 0.484$$

That means that 48.4% of the total pulse energy is maximumly usable to the ablation procsess.

Other portion of the pulse energy is waste energy and does not contribute to the ablation process. Even worse, the waste energy will heat the substrate and lead to undesired effect and influence on the substrate.

In case of given threshold and pulse energy the optimal beam cross section $(2a \cdot b)_{opt}$ for obtaining maximum effective energy efficiency is determined by:

(20) $$(2a \cdot b)_{opt} = \sqrt{\frac{2}{\pi e}} \frac{E}{\phi_{th}}$$

In case of given threshold and spot size $(2a \cdot b)_{spot}$ ablated by each pulse the pulse energy required can be calculated by

(21) $$E = \sqrt{\frac{e\pi}{2}} (2a \cdot b)_{spot} \phi_{th}$$

2.3 Two dimensional top-hat beam

Given a two dimensional quasi top-hat beam with a cross section of $a \cdot b$. The intensity has mainly periodic variation with the maximum fluence $\phi_{\max}$ and the minimum fluence $\phi_{\min}$. The pulse energy and the modulation of the intensity are then given:

(22) $$E = ab \frac{\phi_{\max} + \phi_{\min}}{2}$$

and

(23) $$M = \frac{\phi_{\max} - \phi_{\min}}{2(\phi_{\max} + \phi_{\min})}$$

For thin film ablation the minmum fluence shall be equal to the threshold fluence. Therefore, the effective process energy is given by

(24) $$E_{eff} = ab\phi_{th}$$

The effective energy efficiency for a two dimensional top-hat is then given by:

(25) $$EEE^{2d} = \frac{E_{eff}}{E} = 1 - M$$

In case of perfect two dimensional top-hat beam without modulation the effective energy efficiency is 100%.

3 Over Filling Factor OFF

Fig. 4 shows how an area can be optimally filled with a beam of circular cross section. For a completely ablation there is following relation between the minimum threshold radius and the distance of two laser spots:

(26) $$r_{\min} = \frac{d}{2\cos 30^\circ}$$

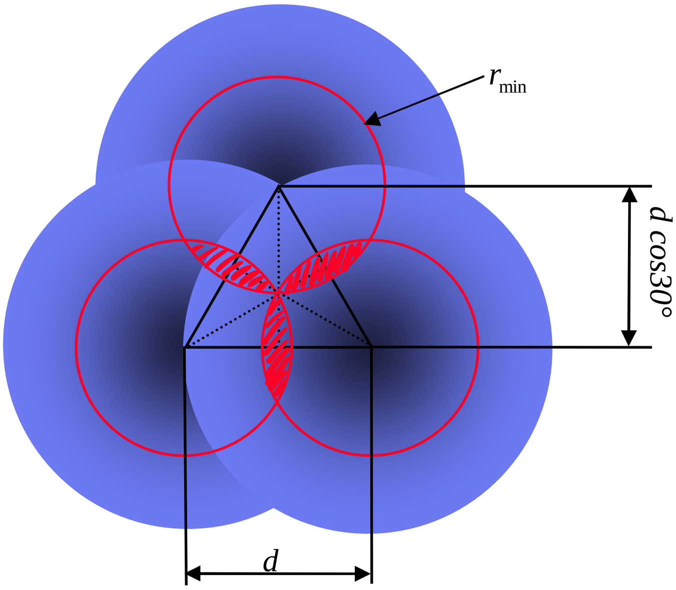

Fig. 4: Filling of an area by a circular beam.

The maximum row distance is equal to $d\cos 30^\circ$. The effective area per laser pulse is given by S_{eff}

(27) $$S_{eff} = d \bullet d\cos 30^\circ$$

The over filling factor is the ratio of the area defined by the threshold radius and the effective area per laser pulse. It is give by

(28) $$OFF_{circ} = \frac{\pi r_{\min}^2}{S_{eff}} = \frac{\pi r_{\min}^2}{d \bullet d\cos 30^\circ} = \frac{2\pi}{3\sqrt{3}}$$

It is obvious that for all beam with rectangular or square cross section the over filling factor is equal to 1.

(29) $$OFF_{rect} = 1$$

4 Effective Overall Efficiency (EOE)

The effective overall efficiency for the ablation process is defined by the ratio of effective energy efficiency (EEE) and the over filling factor (OFF). For a circular Gaussian beam the maximum EOE is given by:

(30) $$EOE_{\max}^{gaus} = \frac{EEE_{\max}^{gaus}}{OFF_{circ}} = \frac{3\sqrt{3}}{2\pi e} \approx 0.30$$

For a one dimensional top-hat beam the maximum EOE is given by:

(31) $$EOE_{\max}^{1d} = \frac{EEE_{\max}^{1d}}{OFF_{rect}} = \sqrt{\frac{2}{\pi e}} \approx 0.484$$

For a two dimensional perfect top-hat beams the maximum EOE is equal to 1. Therefore, two dimensional top-hat beams are the most effective for thin film ablation application.

5 Conclusions

In conclusion we have given the fundamentals of ablation processes by using laser beams of different intensity profiles and cross sections. For characterizing the efficiency of pulse energy for the ablation processes the effective energy efficiency and the effective overall efficiency have been introduced. Dependences of effective energy efficiency and effective overall efficiency on laser beam parameters for circular Gaussian beams, for one dimensional top-hat beams and for two dimensional square top-hat beams are given. The results shows that circular Gaussian beam with a maximum effective overall efficiency of 30% is the most inefficient beam for ablation process. The maximum effective overall efficiency of a one dimensional top-hat beam is 48%. Two dimensional top-hat beam without modulation has 100% effective overall efficiency and is the most efficient choise for thin film ablation process. Also the lowest influence of waste energy during ablation process with two dimensional top-hat beam is expected.

6 References

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