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# Optimisation of direct laser structuring of printed circuit boards

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ABSTRACT

A model-based optimisation of the process of printed circuit board laser structuring is presented. For this purpose, a comprehensive theoretical model of the interaction between the travelling pulsed laser beam and conductive layer, as well as between the laser beam and the induced plasma plume is employed. The model is used to calculate process speed. Based on the process speed determined, the influence of pulse power, duration, and frequency on process speed is analysed. In addition, an optimal range of process parameters with respect to process speed and quality is defined.



## 1. Introduction

The microelectronics industry requires fast, accurate, well controlled and reliable manufacturing processes. For this reason, lasers continue to extend into manifold material processing applications for microelectronics manufacturing. Some operations performed by lasers, such as microvia drilling in high-density circuit boards, are well established, while others are under evaluation or in early stages of development [1]. This also applies to rapid prototyping of printed circuit board (PCB) microelectronic circuits, the basis for fast development of diverse microelectronic applications. For efficient rapid prototyping of PCBs, an accurate and rapid transformation of the design layout into an operational prototype is needed. For the time being, printed circuit board prototypes can be quickly and economically produced in-house by means of many commercial mechanical milling machines or chemical etching. A faster, more reliable and more accurate approach, however, is to perform PCB prototyping by laser.

At present, there are two possible approaches to laser-based PCB prototyping: autonomous direct laser structuring [2,3] and a novel method combining direct laser structuring and the rubout method [4,5]. The first method is suitable for detailed ablation of fine circuitry features, whereas the combined method is suitable for fast removal of large areas. The combined method also employs direct laser structuring. Therefore, regardless of the method used, the quality and efficiency of the prototyping method thus directly or indirectly depends upon the quality and efficiency of direct laser structuring. In general, the quality of direct laser structuring is associated mostly with the quality of line edges and with the heat-affected zone, which are mutually influenced by process parameters of pulse repetition frequency, pulse duration and power. On the other hand, the efficiency of the process is defined by process speed at the required level of quality. One of the parameters that characterises process speed and efficiency is threshold velocity, that is, the velocity of the travelling laser beam at which the vaporised depth is equal to the depth of the conductive layer. For a given conductive layer material, threshold velocity can be influenced by various process parameters. Therefore, to achieve efficient laser-based PCB prototyping, appropriate parameters of laser structuring and their influences must be known in advance.

The intent of this article is to determine the process parameters that maximise laser structuring speed while maintaining process quality. For this purpose, a physical model describing the interaction of the travelling laser beam with the laser-structured material and laser-induced plasma is applied. Using the model, the

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expression for threshold velocity and corresponding process speed is defined. Based on this, the influence of pulsed laser parameters on process speed is analysed, and the maximal laser beam velocity is defined so that ablation through the entire depth of the conductive layer without damage to the substrate is possible. The defined model-based expression for process speed can generally be used for different laser sources and processed materials. However, in the article we have limited our self to the Nd:YAG laser and to commonly used materials in prototyping, namely a thin copper layer pressed onto a thermally and electrically insulating substrate.

## 2. Theoretical model description

In the process of laser beam structuring of PCBs, a layer of copper is selectively removed from the substrate surface by ablation. The main process parameters that influence process speed and process threshold velocity $v_L$ are pulse duration $t_p$, pulse repetition frequency $f$ and average power $P_a$. To perform laser structuring, systems with an average laser beam power of around 10 W, laser pulse duration ranging from nanosecond to microsecond and frequencies from 10 to 200 kHz are usually employed. To define the process parameters at which the highest threshold velocity $v_L$ is achieved, the influence of process parameters on process threshold velocity should be known. For that purpose a model describing the interaction of the travelling laser beam with the copper conductive layer is used. In the following, the physical model, presented in detail in the literature [6], is briefly described and then a model-based expression for threshold velocity is defined.

### 2.1. Model of laser beam-material interaction

Due to the short, high-intensity laser beam pulses used in the process of PCB structuring, the process is usually accompanied by plasma formed of vaporised material from the PCB conductive layer. The model therefore includes the dominant thermal phenomena caused by high-intensity laser beam irradiation of the surface of the conductive layer, which are: heating, melting, vaporisation, ionisation of vaporised material and plasma plume formation [6]. The phenomena included in the mathematical model are strongly coupled. On one hand, heating of the conductive layer by the laser beam causes vaporisation and influences plasma plume formation and laser beam absorption in the plasma. On the other hand, the absorption of the laser beam in the plasma leads to lower laser beam intensity on the surface of the conductive layer and consequently to less efficient conductive layer heating.

In the model, the essential phenomenon of vapor formation is described by the flux of particles $j_s$ leaving the melted conductive layer surface [7]:

$$j_s(T_s) = \frac{\beta p_0}{\sqrt{2\pi k_B m_c T_s}} \exp\left(\Delta H_{lv} \frac{M_c}{R} \frac{T_s - T_{lv}}{T_s T_{lv}}\right). \tag{1}$$

In the above equation, $\Delta H_{lv}$ and $T_{lv}$ are the heat of vaporisation and boiling temperature at ambient pressure $p_0$, $T_s$ is the surface temperature of the conductive layer, $M_c$ is the molar mass of the conductive layer, $m_c$ is the mass of vaporised particles, $\beta$ is the correction factor of vaporisation, $k_B$ is the Boltzmann constant and $R$ is the universal gas constant. As is evident from Eq. (1), the flux of particles $j_s$ depends on the surface temperature $T_s$ of the conductive layer, which can be calculated from the heat equation describing the heating of the conductive layer by laser beam irradiation:

$$\rho_c c_p \frac{\partial T_c}{\partial t} = \nabla \cdot (\kappa \nabla T_c) + Q. \tag{2}$$

In Eq. (2), $T_c$ is the temperature of the conductive layer, $t$ is the time, $Q$ is the laser beam energy source and $\rho_c$, $c_p$ and $\kappa$ are the mass density, heat capacity and thermal conductivity of the conductive layer. Due to the thinness of the liquid layer, the convection of melted material in Eq. (2) is omitted. Furthermore, in the conductive layer, the optical penetration depth for the laser beam is typically very small [8]. Therefore, surface absorption is assumed, and the laser energy source $Q$ is established by boundary conditions [8].

The calculated flux of particles $j_s$ is used for the boundary conditions in the compressible Navier–Stokes system of equations that describe the flow of vapor from the conductive layer, vapor expansion and plasma formation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \tag{3}$$

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \cdot \vec{v}\right) = -\nabla p, \tag{4}$$

$$\rho\left(\frac{\partial E}{\partial t} + (\vec{v} \cdot \nabla) E\right) = -p \nabla \cdot \vec{v} + \nabla \cdot (\kappa_{pl} \nabla T) + \alpha_{pl} I - \varepsilon_{rad}. \tag{5}$$

In the above system of equations, parameters $\rho, \vec{v}, E, p, T, \kappa_{pl}, \alpha_{pl}$ and $\varepsilon_{rad}$ refer to the mixture of vaporised material and ambient gas, and represent mass density, velocity vector, total energy per unit mass, pressure, temperature, thermal conductivity, absorption coefficient and radiation power loss per unit volume. $I$ denotes the intensity of the laser beam in a gas, calculated by the Beer–Lambert law [8]. The thermal conductivity of the plasma $\kappa_{pl}$ is defined by the kinetic theory of plasma [9], whereas the radiation power loss per unit volume $\varepsilon_{rad}$ is calculated using the Bremsstrahlung radiation mechanism [10].

One of the most important parameters that influence the formation and properties of plasma is the absorption coefficient $\alpha_{pl}$, which describes the absorption of the laser beam in the plasma. Most often in laser-induced plasma plume modelling, the absorption coefficient $\alpha_{pl}$ characterises the absorption due to the inverse Bremsstrahlung mechanism only [11]. However, it is known that photoionisation and absorption by small condensed clusters, known as Mie absorption, are also important mechanisms than can contribute to laser beam absorption in plasma [12]. Therefore, in our model the absorption coefficients $\alpha_{ib}, \alpha_{pi}, \alpha_{Mie}$ due to all three mechanisms are considered. The corresponding absorption coefficient of the plasma $\alpha_{pl}$ is defined by the sum of all three coefficients $\alpha_{pl} = \alpha_{ib} + \alpha_{pi} + \alpha_{Mie}$ [6]. It has been shown that by taking all three mechanisms into account the consistency of the modelling and experimental results can be improved [6]. A more comprehensive description of the model, its solutions and experimental verification are given in [6]. In the following, the model is used to calculate the process threshold velocity $v_L$.

### 2.2. Model-based calculation of threshold velocity

To calculate the threshold velocity $v_L$, first the vaporised depth $h$ has to be calculated. In general the vaporised depth $h$ depends on the flux of particles $j_s$ given by Eq. (1). To simplify the definition of threshold velocity and especially to reduce the calculation time of flux of particles, we consider a motionless laser beam impinging perpendicularly on a flat surface. This simplification enables the model to be solved in a three-dimensional system with cylindrical symmetry. In the case of cylindrical symmetry, the flux of particles $j_s$ depends on surface temperature $T_s$, which in addition to time $t$ depends on radial distance $r$. Considering this, the vaporised depth $h(r)$ after the first pulse is given by:

$$h(r) = \frac{m_c}{\rho_c} \int_{t=0}^{\infty} j_s(T_s(r,t))\, dt. \tag{6}$$

Further, results of our experimental and theoretical investigations show that in the case of a motionless laser beam source, the