



# Effects of pulse duration on removal characteristics of silver nanowire transparent conductive film by nanosecond pulsed laser



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## ABSTRACT

In laser processing of silver nanowire transparent conductive film covered with an acrylic resin layer, effects of pulse duration on electrical insulation and surface quality were experimentally investigated by using nanosecond pulsed laser. The minimum laser fluence to achieve the stable electrical insulation by removal of silver nanowire became small with decreasing the pulse duration, but shorter pulse duration showed drastic change of removal trace area of silver nanowires at the boundary region of laser fluence to change conductive state to insulation one. In contrast, longer pulse duration around 200 ns indicated almost constant small removal trace area of silver nanowires, and wide processing window to perform the stable electrical insulation with small removal trace area of silver nanowires can be expected by using a proper long pulse duration in nanosecond pulsed laser processing.

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## 1. Introduction

The transparent conductive film has been widely used for flat panel display, photovoltaic, and touch panel. ITO (indium tin oxide) of transparent conductive oxide has been often used for these products, as reported by Hecht et al. (2011). However, indium as a constituent of ITO has concern in the cost and sustainable supplying of material, because indium is listed as one of the rare materials as mentioned by many authors including Cheong et al. (2014). Moreover, Hu et al. (2010) explained that the higher flexibility of transparent conductive film is required, since mobile computing devices, became smaller, compact, lighten weight and thinner shape. In addition, ITO is a brittle oxide film, and it is weak against the bending motion, and Chen et al. (2002) conducted the experiment to bend ITO film. On the other hand, De et al. (2009) explained that the transparent conductive film with silver nanowires has excellent flexibility, and Gupta (2015) reported that its roll to roll manufacturing process can contribute low cost production. Lee et al. (2008) indicated that silver nanowire achieved higher photo current than the metal oxide in the organic solar cell. Therefore, the

silver nanowire transparent conductive film is expected to replace the ITO film.

In manufacturing processes of the product with the silver nanowire transparent conductive film, the film is coated on a substrate such as glass or plastic film, and electric circuits are formed by selective removal of silver nanowires. In the formation of electric circuit, the environment-friendly and the dry processes without chemicals have attracted the attention of industrial fields compared with the etching as the wet processes. Therefore, the selective removal using laser processing has been attempted for these processes, and it is important to keep the homogeneous transparency at removed area and non-removed one with good insulation state after the removal of silver nanowires. Wipliez et al. (2016) reported that an ultrashort pulsed laser of 532 nm wavelength could obtain good processing results in removal of silver nanowires deposited on polyethylene terephthalate (PET).

In contrast, the usage of nanosecond pulsed laser can contribute the low cost production and good operability of manufacturing devices, and good processing characteristics using a nanosecond pulsed laser of near infrared wavelength can attract industrial usability. There are reports regarding the processing of silver nanowires by nanosecond pulsed laser. Henley et al. (2014) discussed the effect of coating morphology on processing results of silver nanowires by nanosecond pulsed laser of 1064 nm wave-

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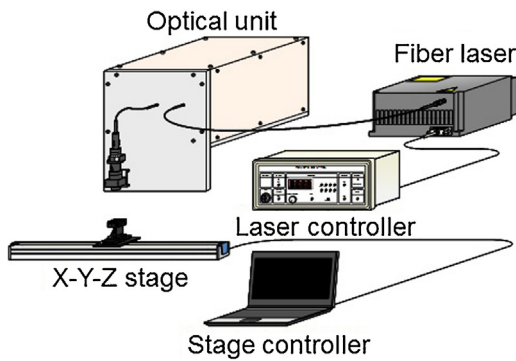


Fig. 1. Schematic diagram of experimental setup.

length. Cann et al. (2016) reported that the touch sensor could be fabricated by selective removal of the deposited silver nanowires on a glass with the nanosecond pulsed laser of 1064 nm wavelength. In addition, Hong et al. (2015) introduced the fabrication method of the touch sensor by nanosecond pulsed laser of 355 nm wavelength, in which the silver nanowires are formed as a film by the vacuum filtration method on a glass. However, these reports did not discuss the silver nanowire transparent conductive films covered with an acrylic resin layer, which is useful for the surface protection and improvement of reliability. It was not reported that a nanosecond pulsed laser could perform good processing results of the silver nanowire transparent conductive film covered with the acrylic resin layer coated on PET.

In the processing by using a nanosecond pulsed laser, it is considered that substrates and overcoat layers of silver nanowire transparent conductive film might be damaged by the thermal removal of silver nanowire with the temperature rise of material. In addition, Spechler and Arnold (2012) reported that light intensity increases at the intersection point of silver nanowires, and the size of nanowire might result in unique phenomena, such as partial removal at the intersection areas. However, the influence of pulse duration on removal traces of silver nanowires has not been clarified in the removal process by a nanosecond pulsed laser of near infrared wavelength yet.

In this study, nanosecond pulsed lasers of 1060 nm wavelength with various pulse durations were irradiated to the silver nanowire transparent conductive film covered with the acrylic resin, and the effects of pulse duration on the surface state and the electrical insulation state in removal process of silver nanowire transparent conductive film covered with the acrylic resin were experimentally investigated using nanosecond pulsed fiber laser. Proper irradiation conditions such as the pulse duration and laser fluence were discussed to achieve better surface appearance with sufficient electrical insulation.

## 2. Experimental setup

### 2.1. Laser irradiation method

Fig. 1 shows the schematic diagram of experimental setup. Three types of nanosecond pulsed fiber laser were used in this experiment to use various pulse duration. The pulse duration of 30 ns, 50 ns, and 100 ns were obtained from one nanosecond pulsed fiber laser. Other two lasers generated “120 ns and 160 ns”, and 200 ns, respectively. These pulse duration was selected to discuss the thermal effect on removal phenomena. The center emission wavelength and the pulse repetition rate were 1060 nm and 50 kHz, for all laser oscillators, respectively. Although the pulse repetition rate of 50 kHz was used, the pulse interval did not affect processing results according to individual irradiation spots with sufficient scanning velocity.

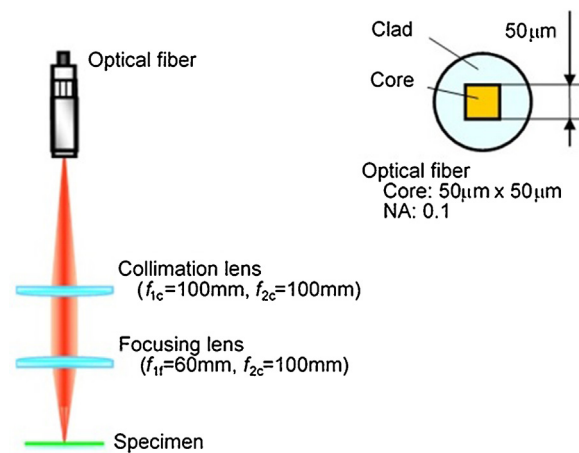


Fig. 2. Optical setup.

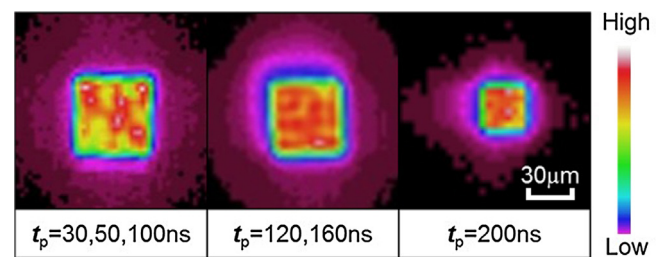


Fig. 3. Beam modes for various pulse duration.

Fig. 2 shows the schematic diagram of optical setup after the optical fiber. Fig. 3 shows the beam modes for various pulse durations. Since Rung et al. (2013) reported that the laser-beam intensity distribution of Top Hat did not do damage to a base material, gaussian mode distribution converted into square-shaped top-hat intensity distribution of laser beam by using the square-shaped optical fiber (Core size: 50  $\mu\text{m}$  square). In the case of pulse duration of 200 ns, the laser beam from the square-shaped optical fiber was focused on the specimen by using a collimation lens of  $f_{1c} = 100$  mm and a focusing lens of  $f_{1f} = 60$  mm in focal length. In this optical setup, 30  $\mu\text{m}$  square spot with top-hat intensity distribution was obtained at the focusing plane. As for pulse duration of 30 ns, 50 ns, 100 ns, 120 ns and 160 ns, the laser beam was focused on the specimen by using the combination of collimation lens and focusing lens of  $f_{2f} = f_{2c} = 100$  mm in focal length. Top-hat intensity distribution was obtained as 50  $\mu\text{m}$  square spot at the focusing plane.

The optical setup with pulse duration of 200 ns was different from that with other pulse durations, since specifications of this laser oscillator required a short focal length in order to obtain the homogeneous top-hat beam mode. Hence, 30  $\mu\text{m}$  square spot was used in the case of 200 ns pulse duration. Although spot sizes were different in pulse duration, the same laser fluence was used in all pulse duration by controlling the pulse energy. The spot size from 30  $\mu\text{m}$  to 50  $\mu\text{m}$  is commonly used for creating electrical circuits of transparent conductive films in industrial applications said by Nakatani (2011).

Transparent conductive film containing silver nanowires was mounted with the jig on X-Y-Z stage in air. The laser spot was scanned on the specimen surface by controlling the feed rate of stage. The feed rate was determined by the combination of spot size and pulse repetition rate to obtain individual irradiation spots. Straight processing line was formed at the overlap rate of 0%, which means no-overlap and no-spacing between pulses.

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