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ORIGINAL PAPER

# Effective design of a precision removal process of ITO thin-films

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**Abstract** This study presents a new modus of electro-removal using a 'design recycle' system offering faster performance in removing the color filter surface Indium–tin-oxide (ITO) thin-films. This system can effectively recycle defective products, thus decreasing both production costs and pollution. For the removal-process, the high rotational speed of the cathode elevates the dreg discharge mobility and improves the removal effect. The high flow velocity of the electrolyte provides increased discharge mobility and better removal effects. A small gap between the cathode and the ITO surface or a higher working temperature corresponds to a higher removal rate of ITO. A faster feed rate of color filters combined with a higher electric current produces a fast removal rate. A pulsed current can improve the effect of dreg discharge and contributes to the achievement of a fast work-piece (color filter) feed rate, but raises the current rating.

**Keywords** Nanostructure · Electrochemistry · Precision recycle · ITO · Thin-films · Surface defects · Semiconductors · Electroremoving

## 1 Introduction

Flat panel LCD displays are now the way of the future, and their rapid development in recent years has made them one of the most important fields in high technology today. TFT-LCD play an extremely critical role, with color filters determining the display of colors. Color filters are the critical components in LCDs since each TFT array is matched to a color filter of the same size. This means that the quality of the color filter has a decisive effect on the LCD's color reproduction [1].

The primary cause of a decrease in yield rate for LCD production is "dust". Dust particles attached to the LCD substrate impair its function, causing breaks in the circuit, short-circuits, or poor performance. Many causes of defects have been found to be related to dust. These defects in the color filter production process include black and white spots or missing colors as well as defects caused by uneven glass substrate [2]. Moreover, when a resin photomask layer is formed on the glass substrate, and R, G and B pixels are deposited to create color filters, problems may occur, including: pixels that are not pigmented; color bleeding due to uneven separation between pixels; an overcoat that is not properly formed, leading to unevenness and rippling; incorrect positioning of the resin photomask layer and RGB/ITO failure to achieve the specified resistance; and defects caused by particles in the manufacturing process (not to mention problems caused by scratches or flaws in the glass substrate itself [3]).

Electrochemical machining (ECM) is suitable for difficult-to-machine materials; plastic or press dies, wire-drawing dies, and optical and electric parts are good examples. The experimental results of Mileham et al. showed that the quality of the machined surface will be influenced by the current density, electrolyte flow rate, and gap width [4]. Bannard correlated the current efficiency with current density and flow rate of the electrolyte. The maximum efficiency varies with the type of electrolyte [5]. $NaNO_3$ was used as the electrolyte to carry out electro-polishing on the die surface. The result showed that the surface roughness of the workpieces decreased with

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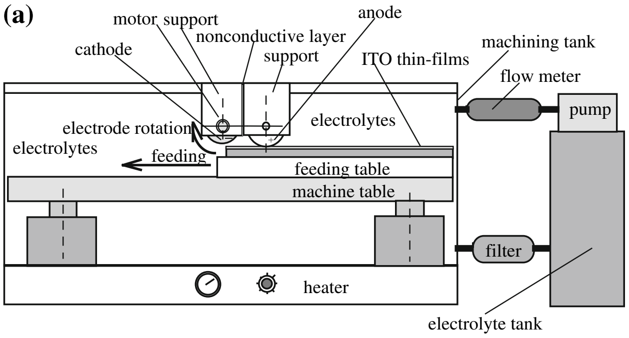
increase in current density [6, 7]. Electropolishing is a surface finishing process that uses PO4-3-P as the electrolyte on brass alloys and zinc alloys. Increasing the zinc content and temperature of the alloy are also found to increase the polishing current [8].

The gap between the electrodes and workpiece directly influences the electrical current condition and dreg discharge [9]. Cagnon et al. showed that the machining resolution is limited to a few micrometers by applying ultra-short pulses of a nanosecond duration; thus, microstructures can be machined by ECM [10]. The ECM process is still under-utilized due to a lack in understanding of the metal removal mechanism and an inefficient tool design methodology. Even for simple cases, it is not possible to predict work profiles accurately [11]. Electrodes of various shapes were developed for electropolishing of a workpiece surface [12], and good surface quality of the workpiece was obtained through careful design of experimental conditions. In ECM, structures taper when the machining depth increases. A disc-type electrode is introduced to reduce the taper [13, 14]. However, the cost and compensation design of tool electrodes remains a major difficulty of electrochemical machining.

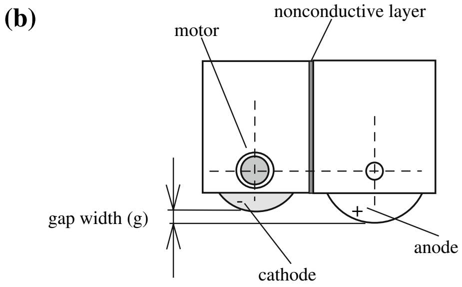
Indium–tin-oxide (ITO) is a transparent conducting material that is deposited as a thin-film on glass substrates for use in optoelectronic devices. The ITO film carrier is a highly simplified semiconductor with a concentration of ~1,020 cm$^{-3}$ with ~$10^{-4}$ Ω cm resistance [15]. This study proposes a new modus of effective form design using electroremoval as a precision recycle-process for ITO thin-films with a design tool-electrode on the surface of TFT-LCD color filters. The adopted precision recycle-process is a highly efficient and low-cost technique. The proposed precision effective form design is developed with both technological and economic considerations.

## 2 Experimental setup and parameters

The effective form design for the process of precision removal of ITO thin-film nanostructures from color filters includes tool electrodes, a DC power supply, a heater, a pump, a flow meter, an electrolytic tank and a filter. The experimental setup is schematically illustrated in Fig. 1a. The tool electrodes (including anode and cathode) are shown in Fig. 1b. The workpiece material was a fifth-generation TFT-LCD panel (for instance, 1,300 × 1,100 mm; 0.7 mm). The workpiece was placed in the electrolytic tank and the soakage bath module in the solutions executed the recycle process. In the current experiment, a design electrode was used and supplied with continuous direct and pulsed current for electroremoval. The electrolytes were NaNO$_3$ of 10 wt.% and PO4-3-P of 5 wt.%. The experimental parameters were the electrolyte temperature, current rating, pulsed period and feed rate of the workpiece (color filter). The amount of material removed from the surface of the color filter after electroremoval of ITO must exceed 150 nm (the average thickness of ITO film is 150 nm in the current study). The current ratings were 75, 100, 125 and 150 A. The feed rate of the workpiece (color filter) ranged from 25 to 475 mm min$^{-1}$. The flow rates of electrolytes were 5, 10, 15 and 20 L min$^{-1}$. The temperatures of the electrolyte were 35, 45, 55 and 65 °C. The dimension of the electrode (cathode) was 25 mm in diameter. The gap width ($g$) between the cathode and the workpiece was 3, 4, 5 and 6 mm. The pulsed period (on/off time) was 100 ms/100 ms. The rotational speed of the electrode (cathode) was 50, 100, 150 and 200 rpm. All workpieces were cleaned with water after the recycling process and then air-dried. The ITO thin-films produced were measured at more than two locations using an Alpha-Step Profilometer (α-step).



System Schematics



Configuration of Tool Electrodes

**Fig. 1** Experimental set-up of electroremoving. (**a**) System schematics. (**b**) Configuration of tool electrodes

## 3 Results and discussion

### 3.1 Requirements of effective form design

The engineering target of the precision recycling process required that the defective ITO thin-films were removed and that the defective color filters were returned to the production line. The effective form design required for the precision recycle-process was made according to the following considerations.

(1) Selective removal of the ITO layer on top of the color filter substrates and reduction of production costs.

(2) Cost reduction is the ultimate goal when establishing systems to recover defective products according to the needs of each Wafer Fabrication. The total recovery of the entire system, which prevents secondary pollution, is just as important as the repair of defective products.

## 3.2 Effective form design experiment

Figure 2 illustrates the gap (*g*) between the cathode and the ITO surface. A small gap (*g*) means a shorter time taken for removing the same amount of ITO since the effect of electrochemical machining is easily developed for supplying sufficient electrochemical power. As far as the stable operation of electrochemical machining and dreg discharge is concerned, an adequate gap width (*g*) of 3 mm was more effective in the current experiment. Figure 3 shows that the removal rate of ITO is improved by increasing the flow rate. The flow rate is increased due to electrolytic deposition, which allows more heat to be dissipated. As a result, the use of a large electrolytic flow rate contributes to the achievement of a fast feed rate of the workpiece (color filter). Figure 4 shows the workpiece under different electrolyte temperatures. As can be seen, a higher temperature corresponds to a higher removal rate for ITO. The higher temperature can be combined with a fast feed rate of color filters to reduce the machining time.

Figure 5 shows that an effective removal is achieved through a combination of current rating and feed rate of the workpiece (color filter) for the process of electroremoving. At a constant current rating, the workpiece has an optimal feed rate for the best removal rate. A fast feed reduces the power delivered to a unit area of workpiece surface, while a slow feed increases it. The former cannot supply sufficient electrochemical power, while the latter will increase the removal time and the cost. In order to reach the same removal amount (150 nm) for the ITO nanostructure, the following combination of parameter values is suggested: 75 A and 300 mm min$^{-1}$, 100 A and 325 mm min$^{-1}$, 125 A and 350 mm min$^{-1}$, 150 A and 375 mm min$^{-1}$. According to Faraday's Law [16]:

$$R = \frac{\eta I T}{F\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \tag{1}$$

where $\eta$ is the efficiency of current, $I$ is the current, $T$ is time, $F$ is the Faraday constant, $n_i$ is the atomic weight, $a_i$ is the proportion of composition and $M_i$ is the atomic valency.

Let $w = R/AT$

$$r = \frac{\eta I}{FA\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \tag{2}$$

and $V = r/\rho$

$$f_m = \frac{\eta I}{FA\rho\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \tag{3}$$

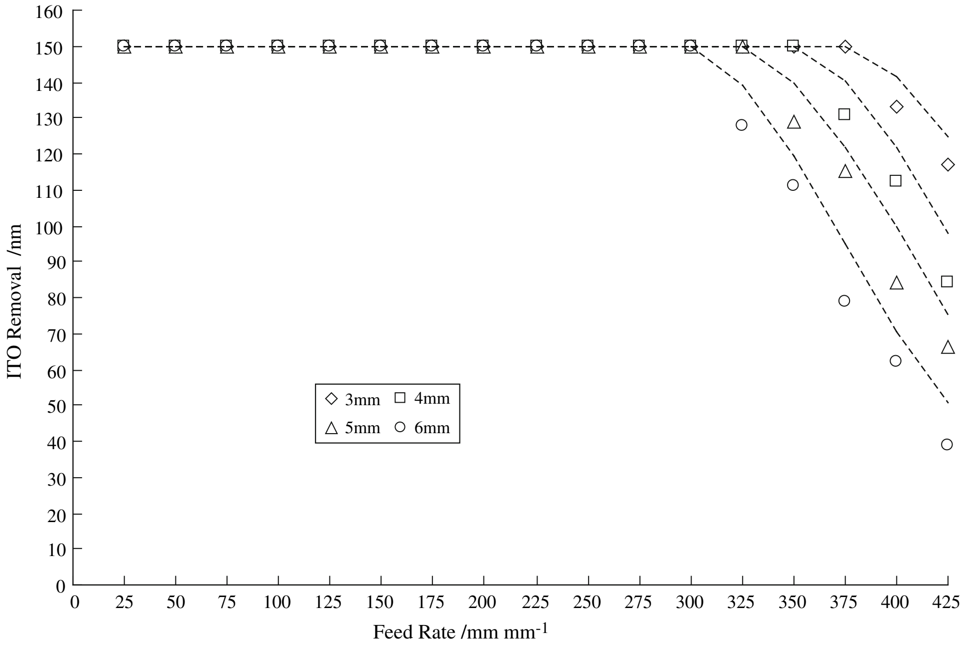


**Fig. 2** Removal amount at different feed rate of workpiece using different gap-width (s) between negative-electrode and ITO surface (NaNO$_3$ of 10 wt.% and PO4-3-P 5 wt.%, 35 °C, 15 L min$^{-1}$, continuous DC 150 A)

**Fig. 3** Removal amount at different feed rate of color filter using different flow rate of electrolytes ($NaNO_3$ of 10 wt.% and PO4-3-P 5 wt.%, 35 °C, continuous DC 150 A)

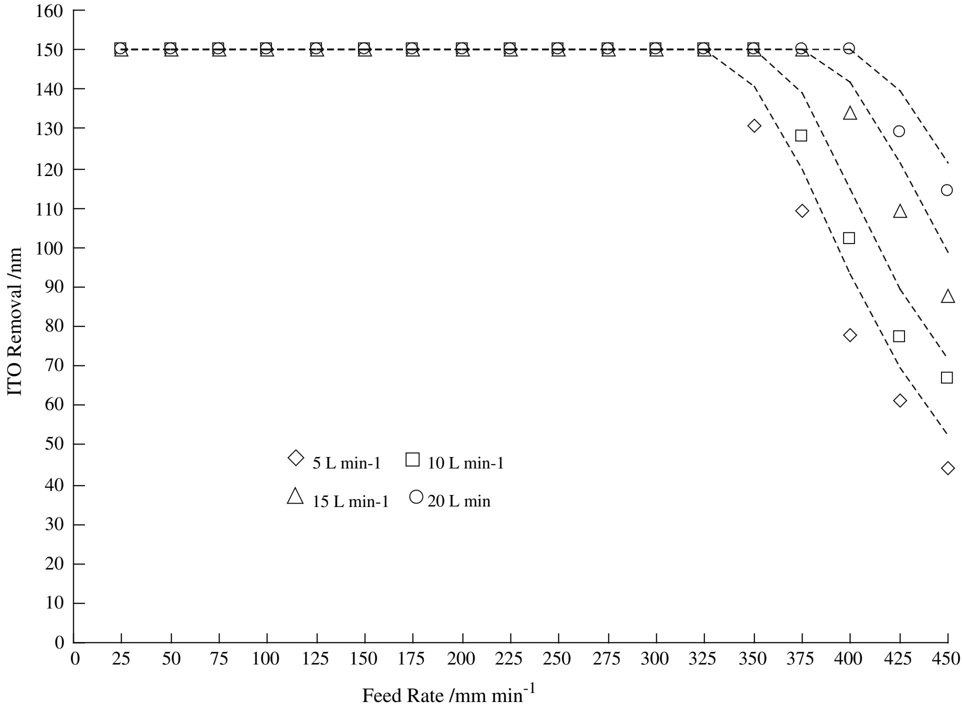
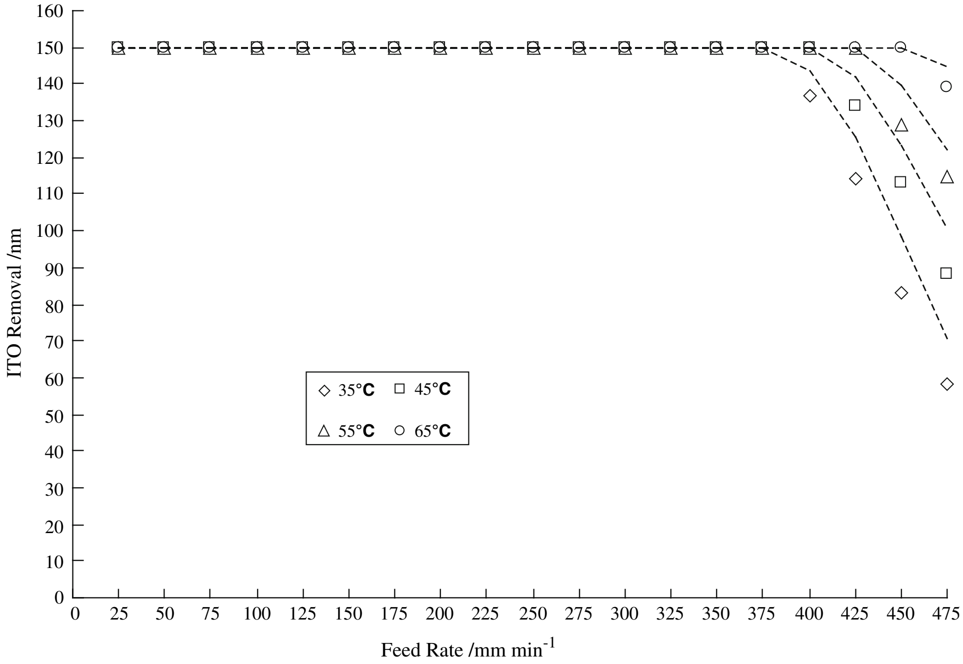


**Fig. 4** Removal amount at different feed rate of color filter using different temperature of electrolytes ($NaNO_3$ of 10 wt.% and PO4-3-P 5 wt.%, 15 L $min^{-1}$, continuous DC 150 A)



where $A$ is the electrochemical machining area, $\rho$ is the density of the workpiece, and $f_m$ is the removal rate in the longitudinal direction. From the above, the theoretical feed rate of the workpiece (color filter) during the same material removal rate can be calculated.

From Fig. 6, one assumes:

$$Y = \frac{d}{2} + g + t \tag{4}$$

where $g$ is the gap width between the electrode (cathode) and surface of ITO (anode); $d$ is the diameter of the electrode (cathode); and $t$ is the removal depth of electroremoval.

$$\cos\theta = \frac{g - t}{g} = \frac{\frac{d}{2} + g}{\frac{d}{2} + g + t} \tag{5}$$

$$(fm)\sin\theta = f \tag{6}$$

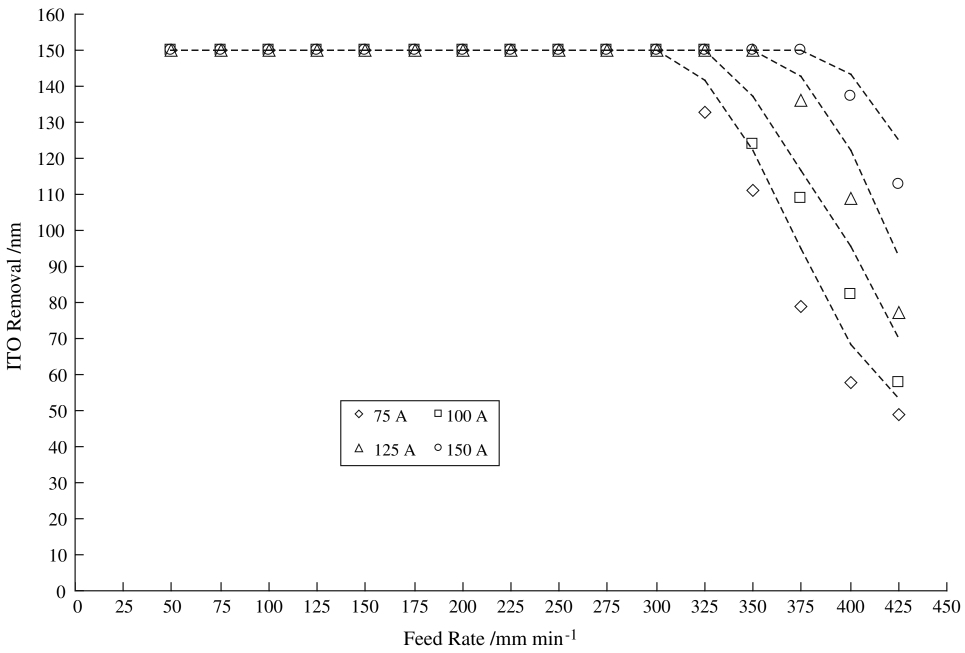


**Fig. 5** Removal amount at different feed rate of color filter using different current rating (NaNO$_3$ of 10 wt.% and PO4-3-P 5 wt.%, 35 °C, 15 L min$^{-1}$, continuous DC)

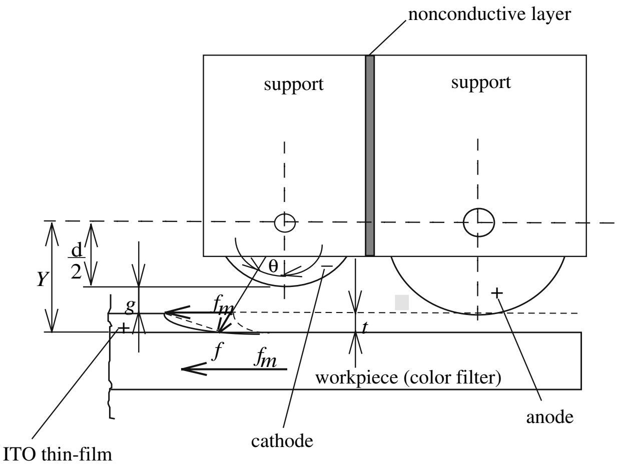


**Fig. 6** Configuration of electrodes and workpiece (color filter)

Squaring and simplifying Eqs. (5) and (6) gives:

$$t = \frac{(d+2g)f^2}{4(f_m^2 - f^2)} \tag{7}$$

where *fm* is the feeding velocity of workpiece and *f* is the removal rate in the longitudinal direction. From Eq. (4):

$$t = \frac{(d+2g)\left[\frac{\eta I}{FA\rho\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)}\right]^2}{4fm^2 - 4\left[\frac{\eta I}{FA\rho\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)}\right]^2} \tag{8}$$

Compared with the experimental results, the removal depth (*t*) is directly proportional to the current rating (*I*), and is inversely proportional to the work piece feed rate (*fm*), which agrees well with the theoretical prediction.

Figure 7 illustrates that a high rotational speed of the cathode produces high rotational flow energy and elevates the discharge mobility, which improves the removal effect. The removal effect is better with a high cathode rotational speed because the dregs discharge becomes easier and is also advantageous to the machining processes. A high cathode rotation contributes to the achievement of a fast workpiece feed rate. Figure 8 shows the effects of the pulsed current. In order to reach the same removal amount (150 nm) for the ITO nanostructure compared with continuous direct current, the current rating needs to be increased proportionately to compensate the off-time. The dreg discharge during the off-time is more complete. This also contributes to the achievement of a fast workpiece feed rate.

## 4 Conclusions

An effective design removal-process for ITO through electroremoval is of major interest. For the removal process, a high electrolyte temperature corresponds to a higher ITO removal rate. The high electrolyte flow velocity provides a larger dreg discharge mobility and a better removal effect. An appropriate gap between the negative electrode and the ITO surface gives a higher removal rate for ITO. A higher current rating with a faster feed rate of TFT-LCD

**Fig. 7** Removal amount at different feed rate of color filter using different rotational speed of electrode (negative pole) ($NaNO_3$ of 10 wt.% and PO4-3-P 5 wt.%, 35 °C, 15 L $min^{-1}$, Continuous DC, 150 A)

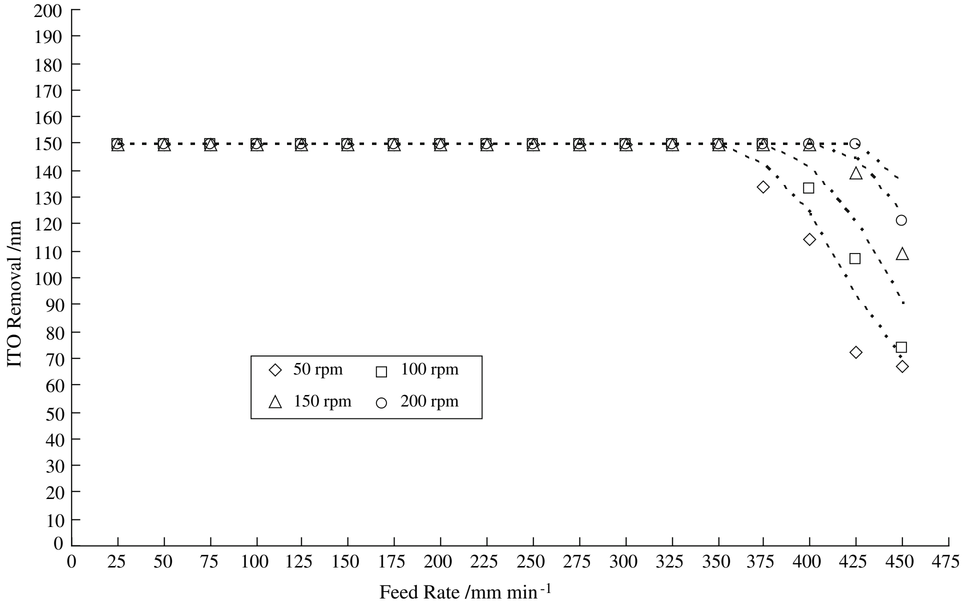
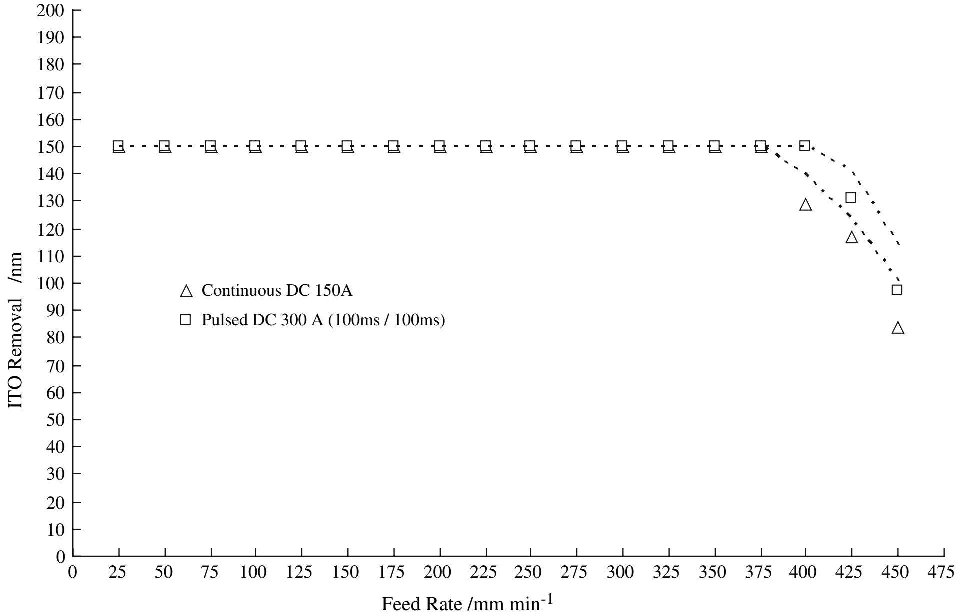


**Fig. 8** Removal amount at different feed rate of color filter using continuous and pulsed direct current ($NaNO_3$ of 10 wt.% and PO4-3-P 5 wt.%, 35 °C, 15 L $min^{-1}$)



color filter effectively promotes a greater removal effect. Pulsed direct current improves the effect of dreg discharge and contributes to the achievement of a fast workpiece feed rate, but increases the current rating. A high cathode rotation speed increases the dreg discharge mobility and improves the removal effect. Through the ultra-precise removal of thin-film microstructures, the semiconductor optoelectronic industry can effectively recycle defective products and reduce production costs.

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