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ORIGINAL PAPER

Precision removal of ITO layer using plate-form tool design

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Abstract An ITO layer is produced using semiconductor techniques, although the defect rate during production is easily seen. Current work presents a new modus of electrochemical machining using a 'design recycle' system offering faster performance in removing the color filter surface's ITO layer. Higher electrical current is not required when an effective feeding electrode is used to reduce the response area. Through establishing an ultra-precise recycling process to remove the thin film microstructure, this helps the semiconductor optoelectronic industry to reduce both production costs and pollution. The design features of the removal processes for a thin film and the tool design of plate-form electrode are of major interest. In the current experiment, the author utilizes a 5th Generation TFT-LCD. The design of tool electrodes is used with continuous and pulsed direct current in the electrochemical machining experiment. High rotational speed of the tool electrodes and high flow velocity of the electrolyte elevates the discharge mobility and improves the removal effect. Pulsed direct current can improve the effect of dregs discharge and is advantageous to associate with the fast feed rate of the workpiece. A color filter with a fast feed rate is combined with enough electric power to provide highly effective removal. A smaller end radius and a thin plate-form positive-electrode provide a larger discharge space and better removal effect. A precision recycling process is presented using an effective plate-form positive-electrode in electrochemical machining. It only needs a short period of time to remove the ITO layer easily and cleanly.

Keywords Semiconductor · Design recycle · Microstructure · ITO · Plate-form tool

Introduction

TFT-LCD plays a critical role in color filters for determining the display of colors. Color filters are the critical component of LCDs, since each TFT array is matched to a color filter of the same size. This means the quality of the color filter has a decisive effect on the LCD's color reproduction. Thus, flat panel LCD displays are now without a doubt 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 [1–2]. Over the past few years, an increasing proportion of the PC monitor market has seen CRTs replaced by LCDs. Elsewhere, panels for mobile phone displays are also a product with excellent growth prospects. The LCD is the most common display now in use in many environments, with TN-LCD panels found in hundreds of electronic products. In the market of LCD applications, however, the largest market by volume and value remains the PC (Personal Computer) monitor market, and the market is still expanding. Among them, the opportunities for LCD panels used in notebook computers have also increased as the market has continued to grow [3]. The reproduction of color imagery in TFT displays is achieved using color filters in concert with a backlighting system. The light from the backlight source passes through the liquid crystal and is controlled by the Driver IC to create a grayscale color source.

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This is then used to illuminate a color filter painted with red, green, and blue color resistors. When passed through the color filter, this results in red, green, and blue light that is recombined within the human eye to form a color image [4]. When the transparent electrode layer of the ITO-film is applied, the procedure is complete. With the push to increase the production capacity of LCD panels, the size of the glass substrate must increase in response; to achieve this, several large glass substrates with pre-formed Color Filters are matched to glass substrates with identical pixel electrode arrays. Liquid crystal is then injected to complete the assembly process [5]. The primary cause of a decrease in yield rate for LCD production is "dust". When these dust particles become attached to the LCD substrate they impair its function causing breaks in the circuit, short circuits, or poor performance. When the causes of defects are examined, many were dust related. Defects caused by particles in the color filter production process include black and white spots or missing colors as well as defects caused by insufficiently even glass substrates. In addition, 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 such as: pixels not being pigmented, color bleed due to uneven separation between pixels, improper forming of the overcoat leading to unevenness and rippling, incorrect positioning of the resin photomask layer and the RGB. Thus, the ITO fails to achieve the specified resistance because of defects or particles in the manufacturing process. The above problems do not include problems caused by scratches or flaws in the glass substrate itself [6–7]. Color filters are critical components in LCDs since each TFT array is matched to a color filter of the same size. This means the quality of the color filter has a decisive effect on the LCD's color reproduction. The future of display technology will be in flat panel monitors, and TFT-LCD will play an important role in this. The purpose of a display monitor is to recreate the real world in front of our eyes so we can enjoy a visual experience of the best possible quality and experience the most accurate representation of information. Displays must have color to achieve this ideal, and it is color filters that give TFT-LCD flat panel monitors their ability to display colors [8].

Electrochemical machining (ECM) is suitable for high-strength and high-melting point alloy. More industrial applications have been realized throughout the decades, such as electrochemical drilling, electrochemical grinding, electrochemical deburring, and electropolishing [9]. ECM is suitable for difficult-to-machine materials. Plastics or press dies, wire-drawing dies, optical and electric parts are good examples [10]. The experimental results of Mileham and others showed the quality of the machined surface is influenced by the current density, flow rate of electrolyte, and the gap width [11]. ECM uses sufficient current density for removing an electrically conductive metal by anodic dissolution when the anode and cathode are separated by a narrow gap containing a high-pressure flowing electrolyte [12]. Bannard correlates the current efficiency with current density and flow rate of the electrolyte. The maximum efficiency varies with the type of electrolyte [13]. In use of NaCl, metal is removed at 100% current efficiency, and the current efficiency is nearly independent of the current density over the anode surface. On the other hand, the aqueous $NaNO_3$ electrolyte can increase dimensional accuracy. Due to the risk of fire, the alternative electrolyte $NaClO_3$ was replaced by $NaNO_3$ [14]. Shen used $NaNO_3$ as the electrolyte to precede the electropolishing on die surfaces. The results showed the surface roughness of workpieces decreases with the increase in current density, flow rate and concentration of the electrolyte. Moreover, polishing with a pulsed direct current is found to be better than a continuous direct current [15]. Electropolishing is a surface finish process using PO4-3-P as the electrolyte on brass alloys and zinc alloys. The polishing current is found to increase proportionately with an increase in zinc content in the alloy and with an increase in temperature [16]. The gap width between the electrode and the workpiece directly influences the electrical current condition and the dreg discharge [17]. Rajurkar and others obtained the minimum gap width based on Ohm [Ohm's?] Law and Faraday [Faraday's?] Law, and the equation of the conservation of energy, beyond which the electrolyte will be boiled in electrochemical machining. Thus, an online monitoring system was proposed [18]. Schuster and others showed the machining resolution is limited to a few micrometers by applying ultra short pulses of a nanosecond in duration, and thus, microstructures can be machined by ECM [19].

The electrochemical machining process is still being under-utilized because of a lack of understanding of the mechanism of metal removal and an inefficient tool design methodology. Even for simple cases, it is not possible to predict work profiles accurately [20]. For electropolishing of external cylindrical surfaces, various electrode shapes were developed, including the disc, ring, turning tool, and arrowhead shapes [21–24]. Good surface quality of the workpiece was obtained through arranging the experimental conditions. In ECM, when the machining depth increases, structures taper. A disc-type electrode is introduced to reduce the taper [25]. However, there is also the major difficulty in electrochemical machining of cost and the compensation design of the tool-electrode. The author conducted a new design modus using electrochemical machining as a 'precision recycle' process of ITO-film with a design tool-electrode on the surface of the color filter. The performance assessment of the design tool-electrode in the electrochemical finishing has been for the greater part discussed. The adopted precision recycle process is highly efficient and low-cost. The development of the proposed process is based on technological as well as economic considerations.

Experiment and parameters of design recycle

The equipment of the ITO-film removal precision recycle process from color filter includes a DC power supply, heater, pump, flow meter, electrolytic tank, and filter. The experimental set-up is schematically illustrated in Fig. 1. The design tool-electrodes (including a positive electrode and negative electrode) are shown in Fig. 2. The workpiece material uses a 5th Generation LCD panel (1,300×1,100 mm; 0.7 mm). The workpiece is placed in the electrolytic tank and uses the soakage bath module in the solutions to execute the recycle process. In the current experiment, a design electrode is used and supplied with a continuous direct current in the electrochemical machine. The electrolyte is $NaNO_3$ of 10 wt% and PO4-3-P 5 wt%. The experimental parameters are the electrolyte temperature, current rating, pulsed period, and feed rate of the workpiece (color filter). The removal reduction from the color filter's surface after electrochemical machining for ITO-film is 150 nm. The current rating is 75, 100, 125, and 150 A. The feed rate of the workpiece (color filter) ranges from 25 to 475 mm/min. The temperature of the electrolyte is 40, 50, 60, and 70°C. The flow rate of the electrolyte is 10, 15, 20, and 25 l/min. The diameter of the positive-electrode is ψ30 mm. The diameter of the negative-electrode (Dn) is 24, 22, 20, 18 mm. The thickness of the positive-electrode (*t*) is 3, 4, 5, and 6 mm. The pulsed period (on/off time) uses 100/100 ms compared with the continuous direct current. The thickness of the positive-electrode (*t*) is 7, 8, 9, and 10 mm. The end radius of the positive-electrode ranges from 2 to 3.5 mm. The rotational speed of the tool electrodes uses 50, 100, 150, 200 rpm. All workpieces undergo water cleaning after the recycle process and are then air-dried. The produced ITO-film is measured at more than two locations byα-step.

Results and discussion

Experiment on basic parameters

Figure 3 shows adequate removal is achieved through combining the current rating and feed rate of the workpiece for the process of electrochemical machining. At a constant current rating, the workpiece has an optimal feed to obtain the best removal rate. A fast feed reduces the power delivered to a unit area of the workpiece surface, and a slow feed increases it. The former could not supply sufficient electrochemical power, while the latter could increase the removal time and cost. To reach the same removal amount of 150 nm for ITO-film, the following combination of parameter values is suggested: 75 A and 300 mm/min, 100 A and 325 mm/min, 125 A and 350 mm/min, 150 A and 375 mm/min. According to the theoretical removal rate formula on alloy from Faraday's Law [12, 15]:

$$w = \frac{\eta I}{FA\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \ldots\right)} \tag{1}$$

where η is the efficiency of current, I is the current, t is time, F is the Faraday constant, n_i is the atom number, a_i is the proportion of composition, and M_i is the atomic mass.

$$Let\, f_m = w/\rho \tag{2}$$

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

where A is the electrochemical machining area, ρ is the workpiece density, f_m is the removal rate in the longitudinal direction. From the above, the theoretical feed rate of the workpiece during the same material removal rate can be calculated. Where η, *I*, *F*, and *A* are regarded as constant for the material.

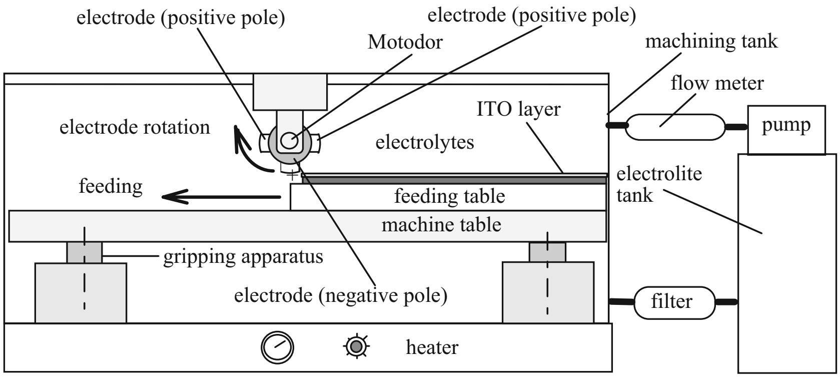
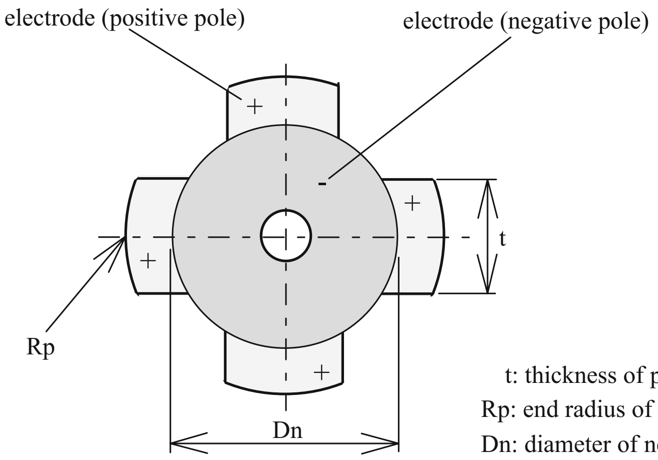


Fig. 1 Experimental set-up of design recycle system



t: thickness of positive-electrode
Rp: end radius of positive-electrode
Dn: diameter of negitave-electrode

Fig. 2 Geometry of design tool-electrodes

From Fig. 4 (configuration of electrodes and workpiece), one assumes:

$$Y = \frac{D_n}{2} + s + h \tag{4}$$

where *s* is the gap between the negative electrode and ITO surface (positive electrode) and *h* is the removal depth (thickness of ITO) of the electrochemical machining.

$$\cos\theta = {(Y-h)}/{Y} = \left(\tfrac{D_n}{2} + s\right)\Big/\left(\tfrac{D_n}{2} + s + h\right) \tag{5}$$

$$\left(V_f\right)\ \sin\theta = f_m \tag{6}$$

squaring and simplifying from Eqs. 3 and 4, one obtains:

$$h = \frac{(D_n + 2s)f_m^2}{4\left(V_f^2 - f_m^2\right)} \tag{7}$$

where V_f is the feeding velocity of the workpiece and f_m is the removal rate in the longitudinal direction. From formula (3), one obtains:

$$h = \frac{(D_n + 2s)\left[{\eta I}/{FA\rho}\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdot\cdot\right)\right]^2}{4V_t^2 - 4\left[{\eta I}/{FA\rho}\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + ..\right)\right]^2} \tag{8}$$

Compared with the experimental results, the removal amount (*h*) of the ITO layer is directly proportional to the current rating (*I*), and is the inverse ratio to the feed rate of the workpiece (V_f). This agrees well with the theoretical prediction.

Figure 5 shows the workpiece under different electrolytic temperatures. The results show a higher temperature corresponds to a higher removal rate for ITO thin-film. One can use the higher temperature to combine with a fast feed rate of color filters to reduce the machining time. Figure 6 shows the removal rate of ITO thin-film is improved by increasing the flow rate. The flow rate is increased due to the electrolytic depositions, which allows more heat to be brought away. As a

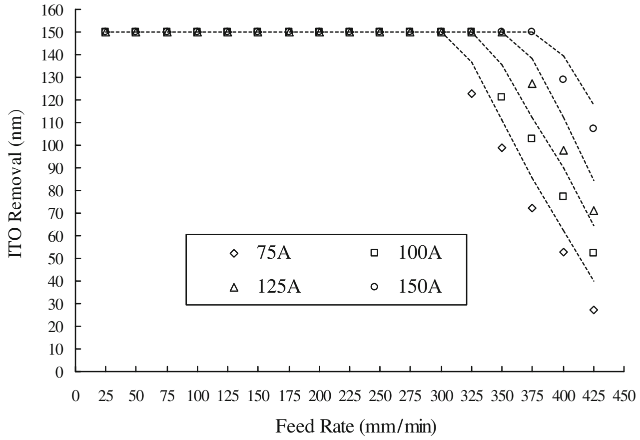


Fig. 3 Removal amount at different feed rate of color filter using different current rating (NaNO$_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, 15 l/min, continuous Dc)

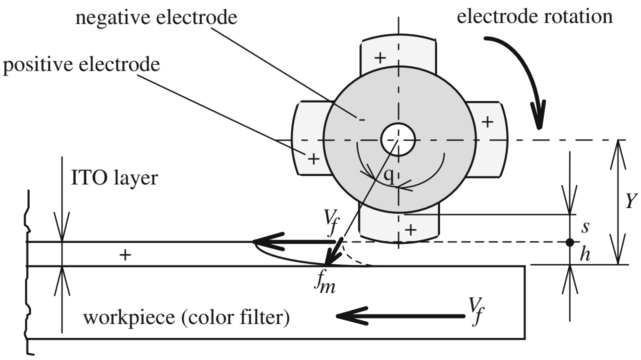


Fig. 4 Configuration of tool-electrodes and workpiece

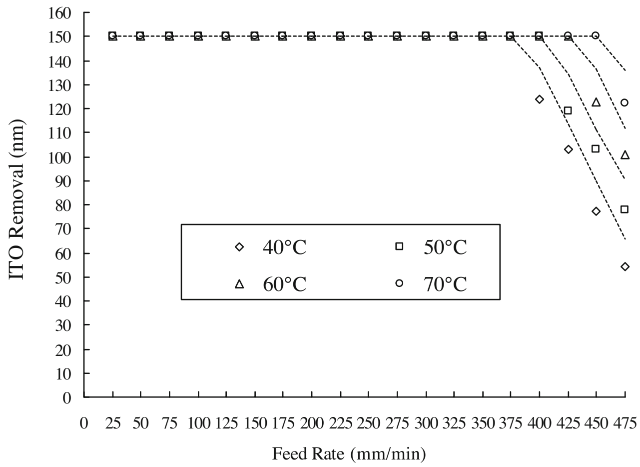


Fig. 5 Removal amount at different feed rate of color filter using different temperature of electrolytes ($NaNO_3$ of 10 wt% and PO4-3-P 5 wt%, 15 l/min, continuous DC 150A)

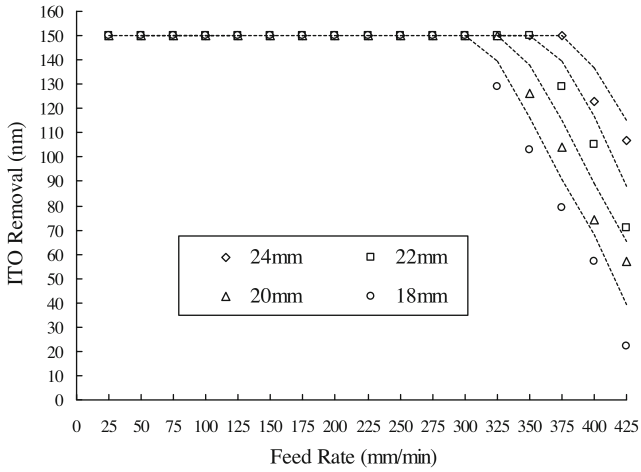


Fig. 7 Removal amount at different feed rate of workpiece using different diameter of the negative-electrode ($NaNO_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, 15 l/min, continuous DC 150A)

result, the use of a large electrolytic flow rate is advantageous to associate with the fast feed rate of the workpiece (color filter).

Performance assessment on tool-electrodes design

Figure 7 illustrates the large diameter of the negative-electrode accompanies the small gap-width between the negative-electrode and the workpiece takes less time for the same amount of ITO layer removal since the effect of electrochemical machining is easily developed for the supplying of sufficient electrochemical power; however, the discharge of electrolytic depositions from the gap is difficult. A small diameter in the negative-electrode accompanies the large gap-width and takes longer since the electrochemical machine is limited. As far as the stable operation of electrochemical machining and dregs discharge is concerned, an adequate diameter of the negative-electrode of 22 mm (gap width 4 mm) is more effective in the current experiment. Figure 8 demonstrated the effects of the thickness of the positive-electrode. Thin positive-electrodes provide higher current density. It also has more open space for dregs discharge, which improves the removal effect. The author adopts 20 mm as the thickness of the positive-electrode in the current study.

Figure 9 shows the effects of the pulsed direct current. To reach the same removal amount of 150 nm for the ITO layer compared with the continuous direct current, the current rating needs to be increased in proportion to compensate for the off-time. One believes the dregs discharge of electrochemical machining during the off-time is more complete and is also slightly advantageous to associate with the fast feed rate of the workpiece. Figure 10 shows the effects of the end radius of the positive-electrode. Decreasing the end

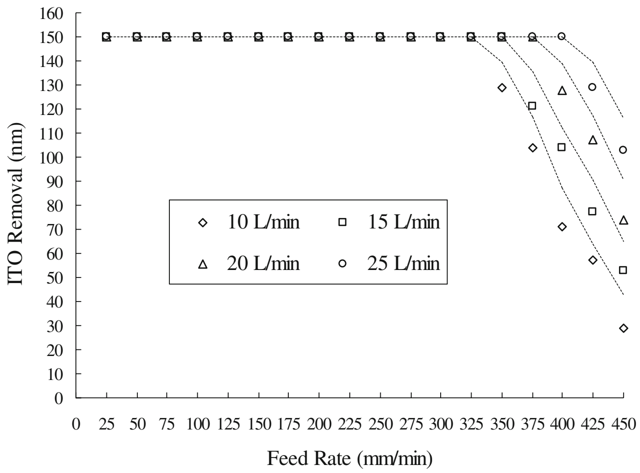


Fig. 6 Removal amount at different feed rate of color filter using different flow rate of electrolytes ($NaNO_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, continuous DC 150A)

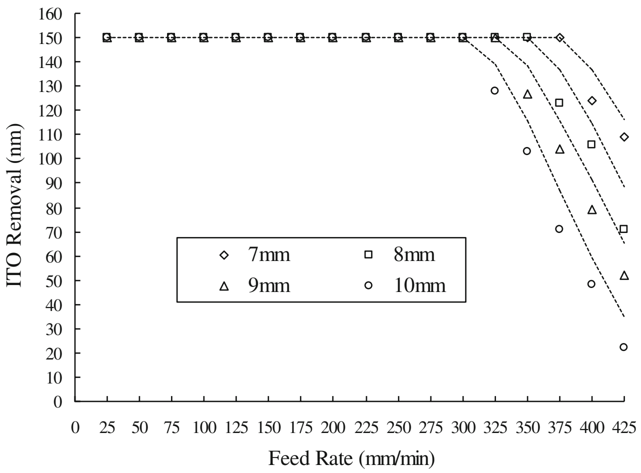


Fig. 8 Removal amount at different feed rate of workpiece using different thickness of the positive-electrode ($NaNO_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, 15 l/min, continuous DC 150A)

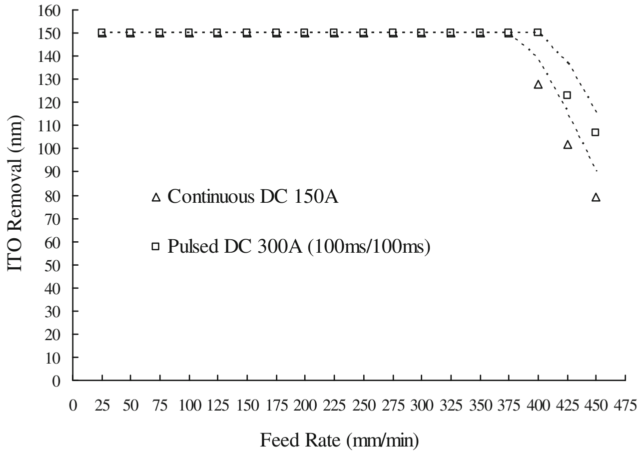


Fig. 9 Removal amount at different feed rate of color filter using continuous and pulsed direct current (NaNO$_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, 15 l/min)

radius is effective to reduce the resistance of dregs discharge and constructs a more effective flushing path along the inclined plane of the wedge. Meanwhile, the electrolytic products and heat can be brought away more rapidly. A small end radius also provides higher current density, which is advantageous for ITO removal. Thus, the smaller the wedge angle, the more effective the removal. Figure 11 illustrates a high rotational speed of the tool electrodes produces high rotational flow energy and elevates the discharge mobility, which improves the removal effect. One believes a high rotational speed of the tool electrodes is advantageous to associate with the fast feed rate of the workpiece (color filter).

Requirements of the design recycle

The engineering specifications require defective ITO layers can be removed and defective color filters can be put back into the production line again. The total recovery of the entire system, which prevents re-pollution, is just as important as the function of repairing defective products. The selective removal of ITO layers on top of color filter substrates will effectively cut down production cost. Cost reduction is the ultimate goal when establishing recovery systems based on each fabricator's need to recover defective products. The color filter recovery process is to be extended to all of the in-house CF fabricators and adopted in their total recovery systems. The requirement of commercialization specifications of the precision recycle-process of ITO layer removal is based on the following considerations:

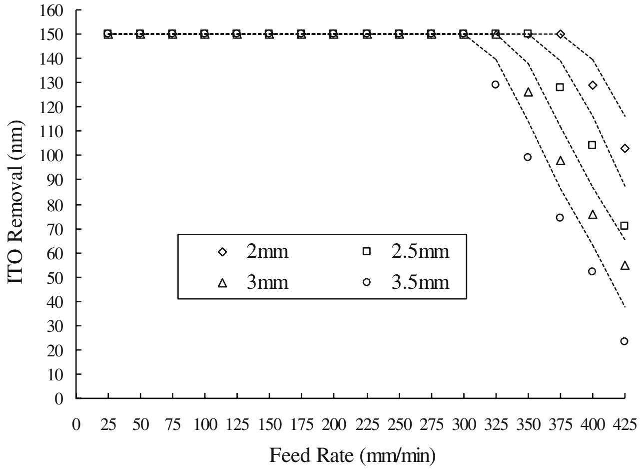


Fig. 10 Removal amount at different feed rate of workpiece using different end radius of the positive-electrode (NaNO$_3$ of 10 wt% and PO4-3-P 5 wt%, 35°C, 15 l/min, continuous DC 150A)

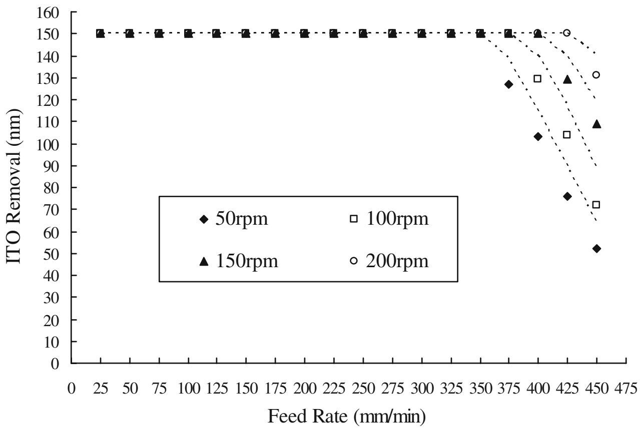


Fig. 11 Removal amount at different feed rate of color filter using different rotational speed of electrode (negative pole; NaNO$_3$ of 10 wt % and PO4-3-P 5 wt%, 35°C, 15 l/min, Continuous DC, 150A)

1. products or technologies derived from implementation of glass recovery systems
2. offers recovery process services to major domestic and foreign fabricators
3. provides an integration of production, equipment, and processing technologies based on this research project, namely, the direct lead-in of technical services into domestic and foreign fabricators and the establishment of recovery process lines depending on the needs of in-house CF fabricators.

Conclusions

Through the ultra-precise removal of thin film microstructure, the semiconductor optoelectronic industry can effectively recycle defective products, reducing production costs. A removal process of ITO-film through electrochemical machining is of major interest in the current study. ITO-film can be removed completely by an adequate combination of color filter feed rate and electric power. For the removal process, high flow velocity of the electrolyte provides larger discharge mobility and a better removal effect. A higher temperature of the electrolyte corresponds to a higher removal rate for ITO-film. A higher current rating with a quicker color filter feed rate effectively achieves fast promotion of the removal effect. A pulsed direct current can improve the effect of dregs discharge and is advantageous to associate with the fast feed rate of the workpiece, but raises the current rating. A thin positive-electrode, a small end radius of the negative-electrode, or a higher temperature corresponds to a higher removal rate for ITO-film.

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