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Investigation of silicon wafering by wire EDM

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The new technology of silicon wafering by wire electrodischarge machining (EDM) was investigated to determine its mechanism of current-conducting and material removal. Target materials were n-type single-crystal silicon ingots with the resistivity of 7–15 cmΩ. It was found that the surface potential barrier of the semiconductors had a dominating effect on EDM cutting speed. Technological experiments were performed to determine the correlation between cutting speed and machining parameters. The machined surfaces were examined by scanning electron microscopy and X-ray energy dispersive spectrometer to test the surface finish and surface impurity. The results obtained show that the technique is effective for silicon wafering.

1. Introduction

Silicon wafering technology is becoming more cost-effective due to well-known international competitive factors. More than 90% of all semiconductor components are made of silicon. At present, conventional inner diameter (i.d.) slicing equipment is still the mainstay of the wafering industry, and it encounters improving limitations because of its mechanically abrasive nature. Electrodischarge machining (EDM) has been proposed as a solution for machining hard and brittle nonmetallic materials since the 1980s [1, 2]. It is suggested in this paper that EDM cutting can be profitably applied as an alternative for some wafering tasks still performed by i.d. sawing. EDM, also called spark erosion machining, is a thermo-electric and material-removal process during which sparks are generated between the workpiece and the electrode. This produces heating of the workpiece so that melting and even evaporation of the material occur. The tool electrode of EDM cutting is a travelling metallic wire of diameter 0.3–0.05 mm. The dielectric fluid is continuously brought into the spark gap by the travelling wire. The nonmechanical nature of the process results in many advantages over i.d. sawing. For example, induced breakages in the edges and sawing traces on the surfaces can be easily prevented. Narrow kerf width of 80 μm and thin wafer thickness of 100 μm can be achieved to save valuable materials or to meet special demands, and thin (~ 200 μm) slices can be obtained from a crystal cut both on the $\langle 111 \rangle$ plane and on the $\langle 100 \rangle$ plane. The large silicon ingot (diameter > 150 mm) can be cut with wire EDM. The example of slicing multi-layer silicon wafers shows one of the distinguished niches of the technique. The EDM cutting tool, here a winding of thin molybdenum wire (100–300 m long), is less costly than that of i.d. sawing, i.e. a saw blade electroplated diamond–nickel on a punched 304 stainless core. Moreover, it is convenient to change the machining performance of EDM cutting to a wide extent for different requirements.

No work has been reported on the possibility of cutting n-type single-crystal silicon by wire EDM. In fact, the silicon ingot cannot be cut simply with a common wire EDM system. The original investigation of this method encountered the difficulty of high electric resistance. The mechanism and remedy of this problem are discussed and presented in this paper. Although the investigation emphasizes the realization of the new technique, it also concerns the technological performance experimentally. Here, a wire cutting mechanism is introduced to meet the demands of massive production. Next, an electrical conduction scheme is designed in accordance with the surface electric behaviour. After realizing the EDM wafering, we conducted versatile experiments to examine the different effects of the thermo-electric process on the material removal rate and surface quality. The results are quite satisfying.

2. Experimental procedure

The experiments were performed on a JO781 WEDM-HS machine. In such a massive production as silicon wafering, the wire travelling rate should be increased to improve the process of debris evacuation and dielectric flushing. In travelling wire EDM, the electrode wire, like an electronic bandsaw, cuts the workpiece on the principle of spark erosion. When the wire travelling rate (TR) reaches 4–16 m s^{-1}, the wire consumption rate increases considerably. In a wire EDM machine with high wire travelling speed, a wire winding mechanism rotating in both directions is set up so that the wire, travelling back and forth, can be repeatedly used until it is worn out. The change of rotating direction is monitored by two stroke switches mounted on the guide of the machine base. The cold-drawn wires are made of molybdenum, a tough and heat-resistant material, with diameters ranging from 0.05–0.14 mm. Either emulsion (volume concentration 5%–18%) or kerosene is used as dielectric fluid. The silicon workpieces are n-type single-crystal ingots (resistivity 7–15 Ωcm), provided by the National Semiconductor Laboratory, Zhejiang University.

The whole system for EDM wafering experiments is shown in Fig. 1. The digital pulse generator provides electric discharge power. The pulse parameters, such as pulse duration (1–256 μs), pulse interval (2–512 μs), peak current (0.1–20 A), open circuit voltage (10–180 V) and discharge current rise time (0–40 μs) are set by an MS-51 microcontroller (8 bit CPU and 8K byte memory). A detection unit which is also monitored by the microcontroller measures the electric discharge parameters (discharge voltage, v_e, and current, i_e). Data are sent to a comprehensive computer system, where they are processed, stored and exported. The discharge voltage, v_e, includes three parts of voltage drop, i.e. the voltage drop of the spark gap, the ohmic voltage drop of the workpiece and the surface drop of contacting bound. The discharge current, i_e, is the electric current flowing through the discharge channels. The material removal rate is almost directly proportional to the average discharge current. These pulse discharge data indicate the spark characteristics and machining performance.

3. Current-conducting scheme

Electrical conductivity, required by EDM cutting, is the main consideration in the technique. Although the electric body resistance of the machined samples is usually less than 30 Ω, the discharge current, i_e, cannot exceed 1.2 A when the open circuit voltage rises to 170 V. The cutting speed remains so slow as to be of little practical value. The actual resistance, arising from the surface potential barriers, turns out to be much greater than the body resistance of the silicon ingot. There are three different conductors in the complex current-conducting system, i.e. metal (steel joint), n-type semiconductor (silicon ingot) and high-temperature plasma (discharge channel). Potential barriers may arise because of the difference in work functions or the surface states of the conductors. The three conductors in the wire EDM system form two contacting peripheries which block the discharge current. Both of the peripheral resistances could be overcome to achieve considerable cutting rate. Two technological measures, surface nickel plating and polarity switching, are available to convert the rectifying contact into an ohmic one or to make the rectifying contact "forward biased". For these two measures the following four possible combinations exist:

1. normal polarity connection (electrode wire (−) pole, silicon ingot (+) pole) with the ingot chemically nickel plated;
2. normal polarity connection without the ingot chemically nickel plated;
3. reversed polarity connection (electrode wire (+) pole; silicon ingot (−) pole) with the ingot chemically nickel plated;
4. reversed polarity connection without the ingot chemically nickel plated.

As shown in Fig. 2, four sets of experiments on current/voltage characteristic were performed to confirm the correct technological combination. In the experiments, the molybdenum wire diameter 0.14 mm was used as the electrode. The sample workpiece was a silicon ingot 150 mm long and 63 mm diameter with the resistivity of 7 Ωcm. The pulse duration and pulse interval were set at 84 and 170 μs, respectively. The emulsion with a volume concentration of 7% was used as the dielectric fluid, and the wire travelling rate was 8 m s^{-1}. In accordance with the experimental results, only Combination 3, shown in Fig. 3, is desirable for cutting the ingot with considerable discharge current. It was confirmed that the contact between the silicon ingot and the discharge channel was a rectifying contact, and that the interface barrier arising from the contact between the metal joint and the semiconductor originates from the work-function difference and the surface state as well. Nevertheless, a practical current-conducting scheme (Fig. 3) was discovered by the experiments. Both reversed polarity connection and surface nickel plating are required here. Deductively, both normal polarity connection and surface nickel plating are required with regard to p-type single-crystal silicon. Discharge current and cutting

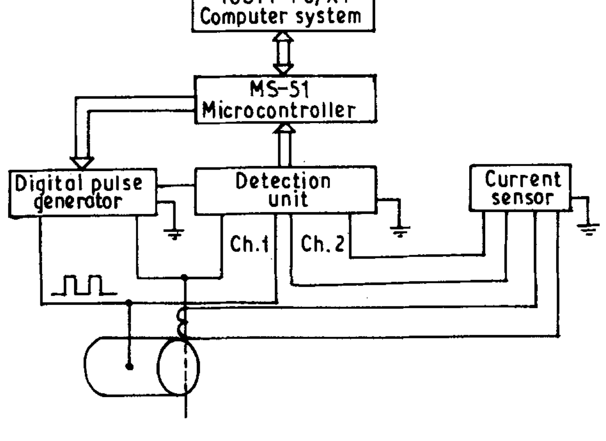

Figure 1 Schematic diagram of the EDM wafering experiment.

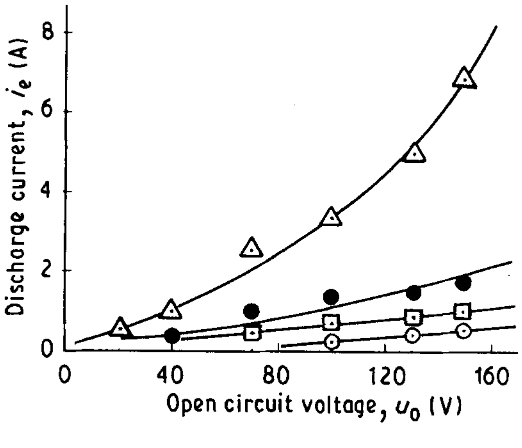

Figure 2 Pulse current/voltage characteristics of the wire EDM conducting system. Cutting width, CW = 10 mm. (●) 1, (⊙) 2, (△) 3, (⊡) 4.

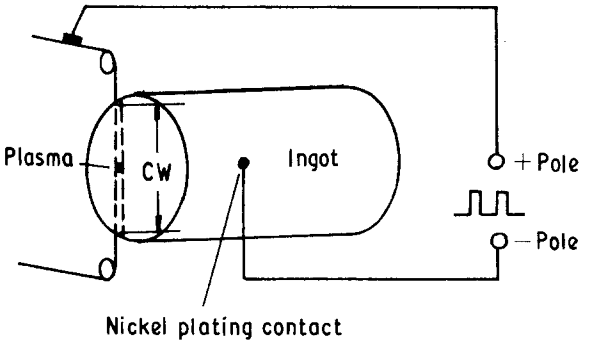

Figure 3 The desirable current-conducting scheme.

speed were significantly increased after the surface potential barriers had been overcome. Moreover, the current efficiency (the ratio of cutting speed to average working current) of cutting silicon is higher than that of cutting steel.

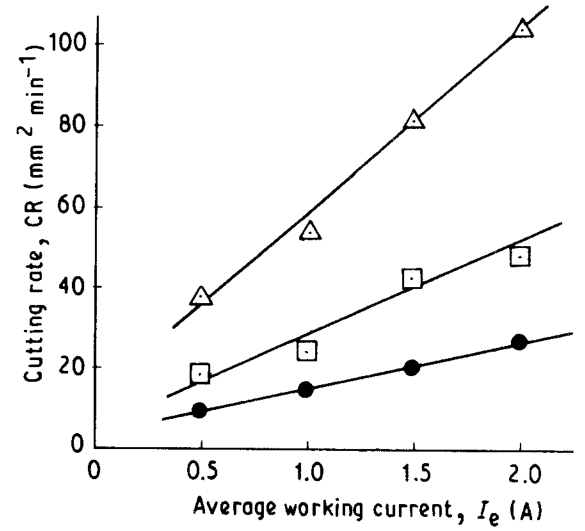

Figure 4 Comparative CR experiments with the dielectrics. CW = 40 mm, t_o = 220 μs, t_i = 70 μs, (●) 3% emulsion, (⊡) 7% emulsion, (△) kerosene.

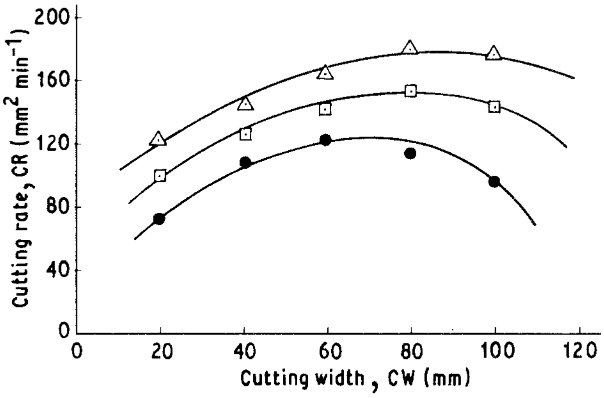

Figure 5 CR experiment: variation of cutting width with wire travelling rate; U_o = 120 V, t_i = 86 μs, t_o = 170 μs, dielectric = kerosene. TR: (●) 4 m s^{-1}, (⊡) 8 m s^{-1}, (△) 15 m s^{-1}.

4. Technological experiments and surface examinations

The outcome of the technique depends on its cutting rate (CR, mm^2 min^{-1}) and surface quality. The total cutting time includes the time that is required for the wire travelling in reverse. Therefore, the actual cutting rate is higher than the cutting rate defined here. Cutting rate is found to be linked with the dielectric fluid and wire travelling rate (TR, m s^{-1}). Fig. 4 shows the comparative CR experiments when using emulsion and kerosene. The machining conditions such as cutting width (CW, mm), pulse duration (t_i, μs), pulse interval (t_o, μs) are also shown in the figure. When kerosene is used as the dielectric fluid, the spark area should be submerged in the fluid to prevent fire. In accordance with the experiments, the cutting rate in kerosene is greater than in emulsion when the average working currents are the same. This is different from the experiments on cutting steel. Different materials require different dielectric fluids. It has been experimentally proved that approximately a 50% increase can be gained by substituting kerosene for emulsion. Fig. 5 shows the CR experiments under varying wire travelling rate and cutting width. There is a non-linear correlation between cutting rate and cutting width, provided other machining conditions are constant. Discharge current will be reduced if the cutting width is too narrow because of the insufficient deionization. On the other hand, the process of evacuation will become worse when the cutting width is too wide. The optimum cutting width is 70–90 mm, varying with the wire travelling rate. Cutting speed increases with increasing wire travelling rate, especially when the cutting width is wide or thick. This is not surprising, because the evacuation process improves as the wire travelling rate increases. The correlations between cutting speed and other machining parameters, e.g. t_o and t_i, remain almost the same as when cutting a steel workpiece, and the cutting rate is approximately directly proportional to the pulse electric power. A high cutting speed of 170 mm^2 min^{-1} and a thick cutting width of 150 mm have been achieved in our experimental wire EDM machine. The reasons for the high cutting rate are the low heat capacity, low thermal conductivity and low density of the material.

Electrode wire wear is increased considerably by the reversed polarity connection, and wire life, which is defined as the total cutting area per wire (usually 100–300 m long), is reduced. It has been confirmed by previous investigations [4, 5] that tool electrode wear is mainly caused by electron current during the initial period after breakdown when the electrode is positively coupled (reversed polarity connection). Therefore, the rise time of the discharge current pulse is extended by the digital pulse generator which has the function of current slope control. The rise fronts of the discharge current pulses incline so that the intensity of electron current and electrode wear can be reduced. Technological experiments on wire life have been carried out to determine the effect of current rise time. Table I shows the experimental results. If current rise time extends to 30 μs, the wire life is increased by five times while the cutting speed is reduced only by 20%. These tactics prove to be effective for coping with wire wear.

TABLE I Current rise time versus wire life and cutting rate

	Current rise time (μs)			
	0	10	20	30
Average cutting rate ($mm^2\,min^{-1}$)	98	92	86	78
Wire life (mm^2)	12,469	24,938	43,641	68,579

Wire diameter 0.14 mm, wire length 220 m, $t_o = 200$ μs, $t_i = 80$ μs, $U_o = 140$ V; dielectric fluid, kerosene; wire travelling rate $10\,m\,s^{-1}$.

TABLE II The machining conditions and surface roughness of the EDM cut samples

	Sample		
	a	b	c
Pulse interval (μs)	220	220	200
Pulse duration (μs)	70	70	70
Discharge current (A)	6	8	14
Cutting rate ($mm^2\,min^{-1}$)	45	69	98
Surface roughness (μm)	1.62	1.74	1.93

Open circuit voltage 120 V, wire travelling rate $10\,m\,s^{-1}$, dielectric fluid 7% emulsion, sample a was cut in the polluted emulsion.

Surface quality is always important, as for the silicon wafers used in electronic devices. Scanning electron micrographs from an EDM cut at low, medium and high cutting speeds are shown in Fig. 6a–c. Their corresponding machining conditions and surface roughnesses are listed in Table II. Note that the surface roughness and microstructure change with cutting conditions. The surface roughness certainly increases with increasing cutting rate. The following list of features could be observed from the micrographs.

1. Drops: ball-shaped pieces of congealed material, scattered on the surface.
2. Islands: long drops of congealed material, attached to the surface.
3. Cavities: holes on the islands, drops on the surface.
4. Cracks: veins in the surface, to be divided into two groups, large and small.
5. Craters: bowl-shaped depressions on the surface.
6. Grains: small cubic pieces, often divided by cracks.

The complex surface topography reveals different material-removal mechanisms which require further investigation.

The surface impurity caused by the electro-discharge process was evaluated by X-ray electron dispersive spectrometry (EDS). Fig. 7a–c are EDS curves showing the surface impurity of the EDM-cut wafers. The corresponding machining conditions are listed in Table II. Polluted dielectric fluid, used in EDM steel cutting, will cause surface impurity, and metallic elements such as iron and chromium will be deposited on the surface (see Fig. 7a). On the other hand, the wire material, molybdenum, may also be deposited on the EDM cut surface. The amount of deposition usually increases with increasing cutting rate (see Fig. 7a–c). To achieve high-quality wafers it is required that a

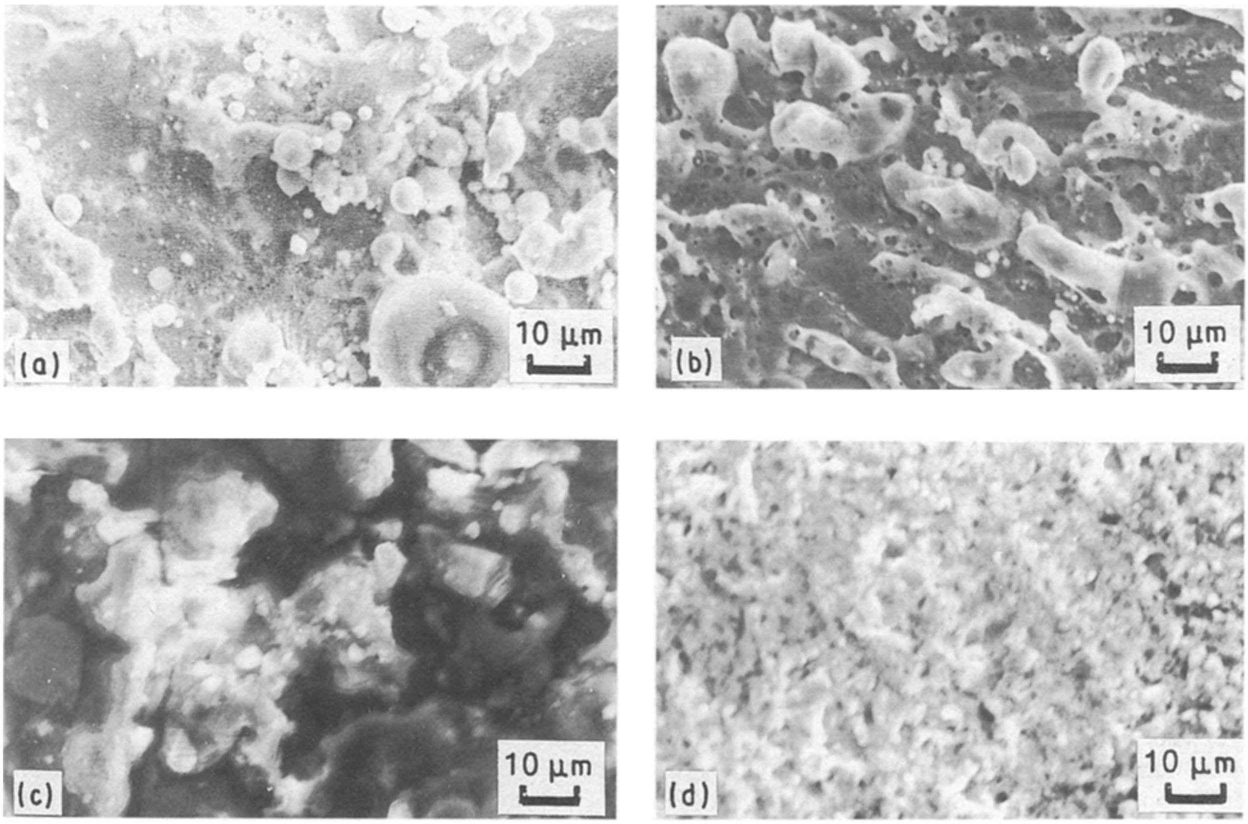

Figure 6 Scanning electron micrographs of silicon wafers cut by wire EDM.

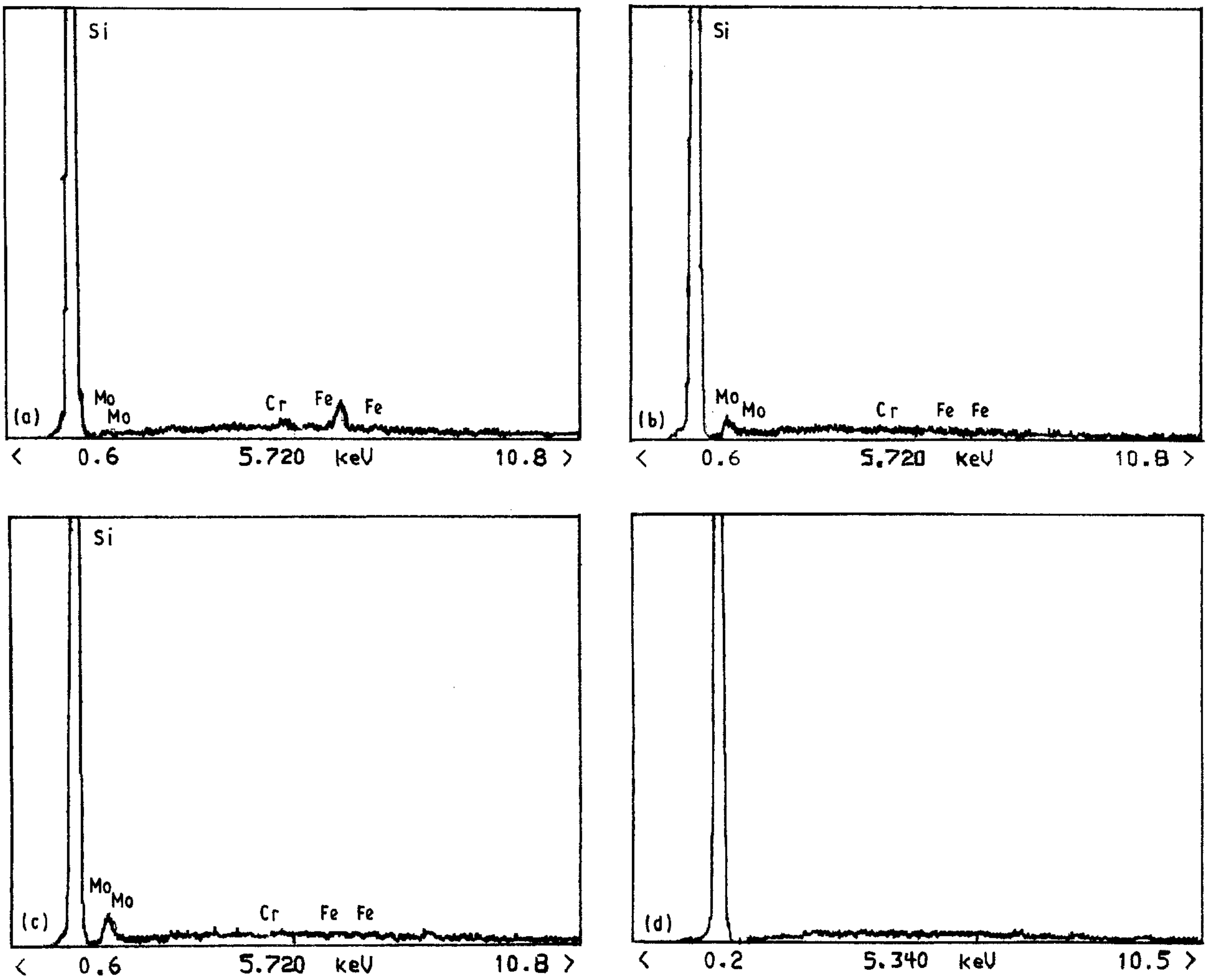

Figure 7 The corresponding X-ray EDS curves.

polishing or lapping process follows the EDM cutting to remove the surface layer. The effects of EDM cutting on surface quality such as surface damage and surface pollution can be completely eliminated after a surface layer 10–35 μm thick has been removed. Sample c is the most severely damaged and polluted (see Figs 6c and 7c). After a surface layer 28 μm thick has been removed, the surface quality is greatly improved. The scanning electron micrograph and EDS curve are shown in Figs 6d and 7d, respectively. Moreover, the machining performance can vary by large degrees. It is easy to achieve a very smooth cut surface by reducing the cutting rate.

5. Conclusion

Based on the preliminary results of the current investigation to determine the feasibility of slicing n-type single-crystal silicon ingots by wire EDM, the following conclusions can be drawn.

1. The surface potential barriers which hinder the discharge current can be overcome by reversing the normal polarity connection and chemical nickel plating on the silicon surface. A considerable cutting speed of 170 $\mathrm{mm}^2\,\mathrm{min}^{-1}$ can thus be conveniently achieved.
2. The cutting speed in kerosene is greater than in emulsion if the silicon ingot is cut under the same average working currents. Cutting speed can be further increased by increasing the wire travelling rate.
3. When an electrode wire is positively coupled in silicon wafering, wire life can be extended by inclining the rise front of the discharge current pulse.
4. The wire EDM cutting process may cause damage and pollution in the surface area especially when the cutting rate is high. The affected surface layer could be removed by a subsequent lapping process.

With wire EDM wafering, thinner wafer thickness, narrower kerf loss and larger wafer size can be achieved. Therefore, it is advisable, in some cases, to use this technique.

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