Article

Directly Writing Patterning of Conductive Material by High Voltage Induced Weak Electric Arc Machining (HV-µEAM)

Zilong Peng 1, Tianming Feng 1, Zilong Wei 1, Yong Zhang 1 and Yinan Li 1,2,*

1 Shandong Engineering Research Center for Additive Manufacturing, Qingdao University of Technology, Qingdao 266520, China
2 Department of Materials Science and Engineering, The Ohio State University, Columbus, 43221 OH, USA
* Correspondence: li.10083@osu.edu or liyinan@qut.edu.cn

Received: 12 July 2019; Accepted: 21 August 2019; Published: 23 August 2019

Abstract: An additive manufacturing (AM) method for the deposition of metallic layer in micron scale on monocrystalline silicon wafer surface by high voltage induced weak electric arc machining (HV-µEAM) has been proposed. The process characteristics of HV-µEAM are analyzed to fulfil the metal material deposition. The influence of the processing parameters on the deposition effect were studied with copper as additive electrode material. Using the optimal parameters, a number of complex trajectory deposition experiments have been carried out and a QD character-type deposition layer with a height of 139.09 µm has been obtained. The deposition has good continuity and high forming precision. It is proven that the new method is achievable and efficient for patterning metallic materials in the micro- and nano-scale on the silicon substrates surface.

Keywords: high voltage induction; arc discharge; deposition; micron scale; metallic layer

1. Introduction

With the further development of lightweight, miniaturization, and functional integration of mechanical products, the application of microstructure and miniature devices with characteristic sizes ranging from nm to mm and with certain functions and patterns has increased at a rapid pace in various areas such as aerospace [1], instrumentation [2], material protection [3], and functional surface [4]. Micro-nanomanufacturing is a necessary means to achieve miniaturization and patterning of products and is an insurmountable and important link in the process of connecting design to application [5]. Patterning and miniaturization metallic materials in the micro- and nano-scale is a core ability for micro/nanomanufacturing technology. Microstructure manufacturing methods have shown diversified development trends. Taking the fabrication of micro-nano devices mainly on silicon substrate as an example, various thin films with different thickness and different properties were grown on silicon substrate by various processes, including radio-frequency magnetron sputtering [6], chemical solution deposition (CSD) [7], and pulsed laser deposition method (PLD) [8], in order to realize the application in micro-electro-mechanical systems (MEMS) [9], optical devices [10] and other aspects. Other forms of manufacturing methods, including selective laser melting (SLM) [11,12], electrochemical deposition [13,14], micro electrical discharge machining (EDM) deposition [15,16], and other methods have achieved certain results in specific processing areas. However, the laser additive manufacturing process has serious heat accumulation, residual stress and other problems that are difficult to control, which make the technology have some limitations [17,18]. Although electrochemical deposition has a principle advantage, the problem of poor localization during processing seriously affects the forming quality [19]. The further development of EDM deposition is restricted by the low efficiency, the small
gap of discharge gap and the poor controllability [20]. Scanning-mode “direct write” patterning of conductive material by (HV-µEAM) can be an alternative route to address these issues.

Studies have shown that the energy generated by the interelectrode discharge can effectively heat, melt, and even gasify the material to be processed [21,22]. Through mechanism analysis [23] and parameter optimization [24], high strength-materials can be easily machined [25]. The interelectrode discharge in the gas medium can realize the loss of the tool electrode and form a certain density of metal deposit on the surface of the substrate material, which can be used for the additive manufacturing of the metal, which is a new type of processing [26]. The selection of the type of discharge energy [27,28], electrode polarity [29], materials [30], and gap medium affects the final processing effect. In order to achieve stable interelectrode discharge and increase deposition rate, domestic and foreign scholars have conducted in-depth research. Jain et al. [31] carried out an attempt to scan and process the metal layer of EDM and found that the accuracy of the deposition layer is difficult to control and the discharge is unstable when the gas medium discharge gap is small. It is proposed to apply a thin layer of solid grease on the surface of the workpiece to increase the discharge gap. Muralidharan et al. [32] introduced permanent magnets and protected them by inert gas in the process of EDM deposition. The direction of magnetic field was perpendicular to the discharge channel. The results show that the deposition height increases with the decrease of width at higher magnetic field intensity. By introducing high density, low ionization energy shielding gas as medium, the influence of ambient air and impurity in the deposition process is eliminated significantly, and the composition of the base material is increased.

The low discharge energy in the EDM affects the machining efficiency and restricts the further development of the technology. Electric arc machining (EAM) and EDM share a similar machining mechanism, but EAM has higher processing efficiency. Scholars have studied EAM from mechanism and experiment. Gu et al. [33] proposed a coupled electrode-plasma-workpiece model to simulate the arc discharging process, compared to the existing EDM and EAM models, which helps to decrease the theoretical error. Zhang et al. [34] found that in the case of electric arc machining (EAM), most of the discharge energy was distributed into the workpiece and the tool electrode, and the energy distributed into anode was much larger than that distributed into cathode. Ahmed et al. [35] found that in hybrid electrical discharge and arc machining (HEDAM), the plasma channel is larger and stable than that of EDM, which influences the erosion efficiency. The result identified that HEDAM had about three times higher removal efficiency than traditional EDM. On the other hand, scholars assisted high voltage to obtain more stable discharge process and better processing effect in the processing process. Zhu et al. [36] found that high frequency and high voltage pulses are beneficial to break down the discharge medium and form discharge channels and higher peak current results in a higher tool wear rate (TWR). Li et al. [37] studied the cracking mechanism of crystals during gas tungsten arc welding, the criterion for crystal cracking formation has been optimized, and verified the validity of the optimized criterion of cracking through experiments with the preheated temperatures of 300 and 500 °C. Now, high discharge density direct current (DC) discharge metal deposition technology is still rare. It is very necessary to study a new metal additive manufacturing technology.

A method of HV-µEAM is proposed in this study. The high voltage (HV) breakdown of the gas medium gap forms a plasma channel, the removal voltage (RM-V) with higher removal current (RM-C) passes through the channel to melt the electrode material compared with the HV, so that it is continuously deposited on the workpiece to form a metal sediment having a certain density. The discharge process and deposition effect of HV-µEAM and HV discharge deposition were compared. The influence of process parameters on the experimental results was studied. By optimizing the process parameters, the sediments with clear contour and good continuity were obtained, which proved that the method can realize metal deposition processing.
2. Materials and Methods

2.1. Materials and Observation Instruments

The workpiece is a silicon wafer with a thickness of 420–520 µm, and resistivity is 20–50 Ω·cm. The tool electrode is red copper with a diameter of 200 µm, and the discharge medium is gas. In order to achieve a higher electrode material removal rate, in this research we focus on negative polarity machining.

The instruments used to observe the deposited material are DSX-510 optical digital microscope (OLYMPUS, Tokyo, Japan) with the maximum observed magnification reach 9000×, BRUKER (VEECO, Plainview, NY, USA) Innova atomic force microscope (AFM), S-3500 N scanning electron microscopy (SEM, Hitachi, Tokyo, Japan) and VHX-2000 Series Ultra Depth of Field 3D Microsystem (KEYENCE, Osaka, Japan) with a large multiplier range from 0.1× to 5000×, enabling detailed analysis from macroscopic stereo imaging to SEM. All specimens were ultrasonically cleaned with ethanol for 20 min before observation.

2.2. Principle of HV-µEAM

Gas has a relatively low relative dielectric constant and is an ideal insulating medium. The principle of discharge is shown in Figure 1. The low voltage is not able to breakdown gas discharge in a large gap, only in a small gap $\delta_1$ breakdown gas discharge (Figure 1a). When a high voltage is applied, a strong distortion electric field is formed in a large range, and at this time, the high voltage can breakdown the gas to form a plasma channel in a large discharge gap $\delta_2$ [38], as shown in Figure 1b. High voltage and low voltage are combined to process arc discharge deposition. The plasma channel formed by the high voltage breakdown gas is used as the bridge of the low voltage passing through and the low voltage parameters (RM-V and RM-C) play a major role in removal.

![Figure 1](image-url) - Schematic of discharge principle and device (a) the gaps of breakdown at different voltages (where $V_H$ is high voltage and $r$ is the radius of electrode), (b) microcosmic diagram of deposition process and (c) the illustration of HV-µEAM.

There is a limit to the dielectric strength of the gas atmosphere, and when applied at HV, the gas loses its insulating properties in a large gap $\delta_2$, forming a conductive plasma channel. An arc is formed when heavy RM-C passes through a plasma channel. When there is an arc between the two electrodes, the end of the tool is heated, melted, and even partially vaporized, and the molten metal forms a droplet at the end of the tool electrode. Under the action of gravity, surface tension and arc blowing force, a certain volume of molten metal droplets are separated from the end of the electrode. The
molten material drops and adheres to the surface of the workpiece, and rapidly cooled and solidified in the gas medium and is connected to the workpiece (Figure 1b). With the progress of the experiment, the deposition layers with a certain thickness are formed on the surface of the workpiece by the continuously deposited deposition materials are bonded to each other. While processing, the X axis and Y axis move in plane to form a deposit layer with a certain shape. During this process, the tool electrode is continuously consumed, and the inter-electrode gap is changed. The Z axis motion is controlled by servo feed mechanism to compensate for the gap.

3. Results and Discussion

3.1. Study on Discharge Process and Deposition Effect

3.1.1. The Discharge Phenomenon of HV

In the process of HV-µEAM, HV breakdown gas discharge is the premise of experiment. It is necessary to study the single discharge of HV before the experiment of HV-µEAM. This experiment is a typical ‘needle-plate’ type severe non-uniform electric field [39]. In the needle-plate discharge model, the discharge begins at the position where the radius of curvature is smaller. Although the end of the electrode is flat, as the experiment progresses, the end surface changes. Therefore, a model of needle end surface as a parabola is used to approximate the calculation of field strength and voltage.

Strong electric field action causes partial ionization of gas and decomposes it into positive and negative electrons [40]. If the electric field strength continues to increase, the number of electrons on the surface of the conductor is doubled, and finally a corona discharge is formed. But at this time, the electrodes have not been broken down. If the stable space electric field is distorted or the distorted electric field continues to increase, the gap will be eventually broken down. Based on the relationship between voltage and electric field strength, Peek has summed up the empirical formula for obtaining the threshold electric field strength $E_c$, that is, Peek formula [41]:

$$E_c = E_0 m \delta [1 + K/(\delta r)^{1/2}]$$  \hspace{1cm} (1)

where $E_c$ is threshold electric field strength, $E_0 = 3100$ kV/m, $m$ is a coefficient describing the surface state of the conductor, $\delta$ is the relative density of air, $\delta = 2.94 \times 10^{-3} \times P/(273 + T)$ (The unit of $P$ is Pa, $\delta = 1$ when $T = 25 \degree C$ and $P = 101325$ Pa), $K = 3.08 \times 10^{-2}$ m$^{1/2}$, $r$ is the radius of the conductor.

Peek formula can also be applied to direct current electric fields [42]. The formula for calculating the maximum electric field strength in the needle-plate model is as follows [43]:

$$E_{\text{max}} = \frac{2V}{r \ln[(2d/r) + 1]}$$  \hspace{1cm} (2)

where $V$ is the voltage between the two electrodes, $r$ is the radius of curvature of the electrode, and $d$ is the gap distance. In order to calculate the corona starting voltage $V_C$, set the maximum geometric electric field strength $E_{\text{max}}$ equal to the threshold electric field strength $E_c$ of the corona discharge, get the formula as follows:

$$E_0 m \delta [1 + K/(\delta r)^{1/2}] = \frac{2V}{r \ln[(2d/r) + 1]}$$  \hspace{1cm} (3)

Assuming $m = 1$, $\delta = 1$, we can get:

$$V_c = \frac{E_0 r}{2} \left(1 + \frac{K}{\sqrt{r}}\right) \ln \left(\frac{2d}{r} + 1\right)$$  \hspace{1cm} (4)

The diameter of the electrode is 200 µm, the discharge gap is 300 µm in this experiment, calculated by Equation (4), the threshold voltage of corona discharge is about 1200 V. The gap breakdown voltage is greater than the threshold voltage of corona discharge, and the breakdown voltage by test is about
1600 V. In order to make the high voltage can break through the gap and form a stable plasma channel, the high voltage value of this experiment is selected as 2000 V. The test results show that this parameter can meet the experimental requirements. HV parameters as shown in Table 1.

**Table 1. HV parameters.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>2000</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>Discharge gap (µm)</td>
<td>300</td>
</tr>
</tbody>
</table>

When a HV is applied between the two electrodes, a distorted electric field is generated between the electrodes. The discharge state is shown in Figure 2. In the microscopic state, the electrode end surface is not flat, the inter-electrode gap of the convex portion is the smallest, and the dielectric strength is the lowest, and the discharge starts from these parts first (Figure 2b). At the beginning of discharge, the discharge range is concentrated around the raised part, the diameter of discharge channel is small and the arc is unstable. As the discharge progresses, the convex portion is etched away, the end surface becomes flatter. The discharge channel extends to the whole end surface (Figure 2c), and the arc discharge is stable. When the high-voltage power supply is turned off, the electric field between the poles disappeared, the positive and negative ions in the plasma channel are neutralized, and the process of deionization is carried out. The macroscopic phenomenon is that the arc is gradually extinguished (Figure 2d,e).

![Figure 2](image-url)  
**Figure 2.** The discharge process of HV (a) before discharge, (b) discharge begins, (c) discharging, (d) arc weaken, (e) arc is gradually extinguished, and (f) end of discharge.

### 3.1.2. The Discharge Phenomenon of HV-µEAM

Although HV-µEAM is accomplished instantaneously, there is still a sequential process. When the gap is adjusted between $\delta_1$ and $\delta_2$, the low voltage cannot break through the gas, and the high voltage plays a leading role in the discharge process. When two kinds of voltage are added between the two poles, the initial stage of discharge is the same as when the HV alone. The difference is that when the HV breaks through the gas to form the plasma channel, the RM-V and high RM-C pass through the channel, which makes the discharge channel expand and discharge more intense. Experimental parameters as shown in Table 2.
Table 2. HV-µEAM parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (V)</td>
<td>2000</td>
</tr>
<tr>
<td>Current of HV (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>RM-V (V)</td>
<td>110</td>
</tr>
<tr>
<td>RM-C (mA)</td>
<td>150</td>
</tr>
<tr>
<td>Discharge gap (µm)</td>
<td>300</td>
</tr>
</tbody>
</table>

In order to observe the discharge process of RM-V, the HV is first turned on and then the RM-V is turned on. The discharge state is shown in Figure 3. When the HV is turned on, the gas is broken down and form a plasma channel. At this time, only the HV alone and the arc radius is small (Figure 3b). When the RM-V is turned on, the high current passes through the discharge channel, which expands the radius of the channel, enlarges the arc spread angle and makes the discharge more intense (Figure 3c). When the HV is turned off, the RM-V cannot break through the gas, and the discharge channel radius decreases (Figure 3d). The current is not flowing smoothly until the arc is extinguished, and the discharge process ends.

3.1.3. The Deposition Effect

Ideally, HV only breaks through the gas to provide a plasma channel for RM-V without participating in material erosion, but HV inevitably participate in material erosion during the experiment. In order to verify the effect of HV discharge deposition on the whole deposition process, the deposition effects of HV discharge alone and HV-µEAM of 10 s were compared. The deposition effect is shown in Figures 4 and 5.
It can be seen from Figures 4 and 5 that when the HV discharge is deposited, the deposited layer has a relatively uniform texture and the sediment color is relatively bright and has a certain porosity. Compared with the deposition point of HV-\(\mu\)EAM, the deposition layer is thinner and the diameter is bigger when HV alone. Under the condition of HV-\(\mu\)EAM, the edge of the deposit is irregular. The height of the deposit is higher and the number of pores per unit area is larger than that of HV discharge alone as its energy is larger than that of using HV discharge. It can be seen that the function of HV discharge is to increase the degree of ionization in the discharge gap for inducing the micro arc from the low voltage.
3.1.4. Energy Dispersive Spectroscopy (EDS) Analysis

The EDS analysis of HV single discharge deposition, HV-μEAM in air and blowing nitrogen HV-μEAM for 10 s was carried out respectively. In addition, multi-layers deposition experiments were carried out to elucidate the increase of deposition material content with the increase of layers using the parameters shown in Table 2. The layer scanning speed is 5 μm/s and scanning distance is 1 mm. The EDS test results are shown in Figure 6.

![Figure 6. SEM image and EDS analysis of deposition, (a) HV single discharge deposition in gas atmosphere, (b) HV-μEAM in gas atmosphere, (c) HV-μEAM under the condition of blowing nitrogen, and (d) Cu contents with different deposition layers.](image)

It can be seen that the deposition layer is thin for the 10 s deposition, which belongs to the overlapping layer of metal layer and silicon wafer. The elements of the deposition layer are mainly Si, Cu and O. Compared with the HV discharge deposition alone, the copper content of HV-μEAM was increased, which proves that the HV-μEAM efficiency is higher than the HV single discharge. The content of oxygen element decreased obviously HV-μEAM under the condition of blowing nitrogen compared with the HV-μEAM in gas. It can be concluded that with the deposition process going on, the content of Cu will increase to form a micro scale copper layer as the additive material copper used in nitrogen or inert gases and the content of copper increases with the increase of deposition layers.

3.1.5. Deposition Models

In order to study the characteristics of deposition process, the morphology of sediments deposited by discharge deposition for 2 s was observed by atomic force microscope (AFM). The end of the
electrode is melted during discharge. Droplets of molten metal, accelerated by electric and gravitational fields, randomly scatter across the surface of the workpiece and rapidly cool (Figure 7a). The molten metal droplets have not enough time to grow around the formed nucleation as grains in the extremely fast cooling speed, resulting in the obtained deposition points with micro/nano scale.

![Figure 7. Schematic diagram of voids formation (a) particles randomly scatter, (b) particles gathered, (c) forming local voids, and (d) 3D-AFM image of deposition.](image)

When the deposition process continues, the deposited particles gather preferentially around the deposited points (Figure 7b), making the surface of the workpiece uneven. The discharge gap of the raised portion ($\delta_3$) is smaller than the recessed portion ($\delta_2$). The change of discharging gap makes the electric field distortion between them more serious and $E_3 > E_2$. Due to the change of the electric field intensity, the deposited particles are more likely to accumulate in the areas with stronger electric field intensity, and the island-shaped depositions are gradually formed, and the island-shaped depositions are connected to each other and the voids are gradually formed (Figure 7c,d). Different from the welding arc whose current density is generally larger than that of 80 A/mm² [44], the current density of HV-µEDM is only 0.76 A/mm². This also determines that the electrode is gradually removed during the discharge process, rather than the electrode and the workpiece being severely ablated, as is the case with welding, and the workpiece and the electrode are melted and flowed to form a molten pool.

Since the tool electrode is depleted in the deposition process, the initial growth position of the deposition material, that is, the upper surface of the workpiece material is taken as the reference surface. The electrode loss length $L_0$ can be obtained by measuring the coordinates of the spindle position before and after machining, and the electrode loss $V_E$ can be calculated. The discharge gap in the touch perception is considered to be equal. The measurement model is shown in Figure 8.

$$L_0 = Z_1 + (Z_2 - 3Z_3)/2 \quad (h_0 < d_0/2) \quad (5)$$

$$L_0 = Z_1 - Z_3 + d_0/2 \quad (h_0 \geq d_0/2) \quad (6)$$
where \(Z_1\), \(Z_2\) and \(Z_3\) are the spindle coordinate, \(h_0\) is the height of deposition, and \(d_0\) is the diameter of electrode.

**Figure 8.** Measurement method of electrode loss by HV-\(\mu\)EAM.

Figure 5a shows that the shape of the point deposition is approximately to a part of the sphere, and the cross section can be regarded as a part of the circle, the following model is proposed (Figure 9). The point deposition and line trajectory can be separately approximated as part of a cylinder and cuboid, and the ratio of the volume \(\Delta_1\) and \(\Delta_2\) was the ratio of the cross-section, scilicet, \(\Delta_1 = S_1/(L_P \times h_0) \times 100\%\) and \(\Delta_2 = S_3/(L_L \times h_0) \times 100\%\), where \(S_1\) and \(S_3\) are the cross-sectional areas of deposition respectively, \(L_P\) and \(L_L\) are the cross-sectional widths of deposition respectively. The volume of point deposition \(V_P\) and the volume of line trajectory deposition \(V_L\) could be expressed as \(V_P = V_{Cy} \times \Delta_1\) and \(V_L = V_{Cu} \times \Delta_2\), where \(V_{Cy}\) and \(V_{Cu}\) were the volume of cylinder and cuboid. In order to express the utilization of materials conveniently, the concept of deposition ratio \(k\) is put forward here, \(k = V_D/V_E \times 100\%\), where \(V_D\) is the volume of deposition.

**Figure 9.** Three-dimensional model of deposition and cross-sectional model of deposition (a) point deposition model and (b) line trajectory deposition mode.

3.1.6. Single Point Multi-Layer Deposition

In order to study the effect of single point multi-layer deposition, deposition experiments were carried out. The electrical parameters are shown in Table 3.
Table 3. HV-µEAM parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (V)</td>
<td>2000</td>
</tr>
<tr>
<td>Current of HV (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>RM-V (V)</td>
<td>110</td>
</tr>
<tr>
<td>RM-C (mA)</td>
<td>150</td>
</tr>
<tr>
<td>Discharge gap (µm)</td>
<td>300</td>
</tr>
</tbody>
</table>

When HV-µEAM single point multi-layer deposition, the electrode position of the workpiece is kept unchanged. Measuring the deposition height by changing the deposition time. The measurement results are shown in Figure 10. It can be seen from Figure 10 that the height of the deposit increases with the deposition time, and the deposition rate is relatively stable.

![Figure 10. Deposition height and deposition rate at different discharge times.](image)

3.2. Effects of Different Parameters on Deposition

It is known from the previous experiment that the method of HV-µEAM can realize the deposition of points, based on which a deeper exploration is conducted. The effects of different parameters on deposition ratio and deposition effect were analyzed. The experimental parameters are shown in Table 4.

Table 4. HV-µEAM parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (V)</td>
<td>2000</td>
</tr>
<tr>
<td>Current of HV (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>RM-V (V)</td>
<td>70, 90, 110, 130, 150</td>
</tr>
<tr>
<td>RM-C (mA)</td>
<td>60, 90, 120, 150, 180</td>
</tr>
<tr>
<td>Discharge gap (µm)</td>
<td>70, 100, 200, 300, 400</td>
</tr>
<tr>
<td>Scanning speed (µm/s)</td>
<td>5, 20, 35, 50, 65</td>
</tr>
<tr>
<td>Scanning distance (mm)</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2.1. The Effect of RM-V on Deposition

The effects of RM-V on electrode loss volume, deposition ratio and the deposition microstructure were studied in this experiment. The deposition effect is shown in Figure 11.
When the voltages are 70 and 90 V, the amount of electrode loss is small, and the continuity of the deposited layer is poor, which is due to the low energy at this time, resulting in less electrode melting. When the voltage is 110 V, the deposition has good continuity and uniform distribution of microstructure. Although the amount of electrode loss is large when the voltage is 150 V, the deposition ratio is small, the deposition profile is irregular, and the surface uniformity is poor. This is because with the increase of voltage, the discharge energy increases and the amount of electrode loss increases, but at the same time, the amount of spatter of the deposited material increases and the utilization of material decreases. Therefore, when selecting the voltage, it should be selected near 110 V.

3.2.2. The Effect of RM-C on Deposition

The effects of RM-C on electrode loss volume, deposition ratio, and deposition microstructure were studied, the results shown in Figure 12. With the increase of current, the amount of electrode loss increases. The color of deposition layer becomes darker and the continuity improves, but the deposition ratio decreases. When the current is 60 mA, the discharge energy is small, resulting in smaller electrode loss volume and deposition volume. The deposition layer is not dense, and part of the location is exposed to the silicon-based surface. At 150 and 180 mA, the deposition layer was continuous. But at 180 mA, the discharge is energy too large, the deposition ratio is small and the material utilization is low. Therefore, when selecting the current, it should be selected near 150 mA.

3.2.3. The Effect of Scanning Speed on Deposition

Figure 13 was the effect of different scanning speeds on deposition. The results shown that with the increase of the moving speed of the electrodes, the loss of the electrodes decreases significantly. When speed exceeds 35 µm/s, the most part of the surface of the silicon wafer is exposed. At a speed of 20 µm/s, the microstructure is unevenly distributed and the continuity of the deposition layer is poor. At a speed of 5 µm/s, the continuity of the deposition layer is better. By comparison, it is preferable to select the scanning speed in the speed of 5 µm/s.
Figure 12. The effect of RM-C on electrode loss volume and deposition ratio.

Figure 13. The effect of scanning speeds on electrode loss volume and deposition ratio.
3.2.4. The Effect of Discharge Gap on Deposition

In this part, the effects of discharge gap on deposition were studied, the results are shown in Figure 14. The electrode loss increases first and then decreases with the increase of discharge gap. When the discharge gap is 70 µm, the deposition layer is discontinuous. This is because the gap is too small, short circuit will occur during deposition, and a fixed-length experiment cannot be completed. Moreover, only part of the end surface of the electrode is melted, so that the width of the deposit layer is much smaller than the diameter of the electrode. When the discharge gap is 100 µm, the discharge is more severe, the sediment layer is destroyed and the color is darker. When the discharge gaps are 200 and 300 µm, the deposition layer has uniform distribution and good continuity. When the discharge gap is 400 µm, the distribution of deposition is uneven and the deposition ratio is small. Therefore, the deposition effect is ideal when the discharge gap is between 200 and 300 µm.

![Figure 14. The effect of discharge gap on electrode loss volume and deposition ratio.](image)

3.3. Deposition Experiment of Complex Trajectory of HV-µEAM

The experiment in the last section shows that the method can be used to deposit continuous linear with good deposition effect. In order to further verify the feasibility and flexibility of the method, according to the experimental results of the previous sections, the experimental parameters were optimized and the experiments of complex trajectories were carried out. Experimental parameters as shown in Table 5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (V)</td>
<td>2000</td>
</tr>
<tr>
<td>Current of HV (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>RM-V (V)</td>
<td>110</td>
</tr>
<tr>
<td>RM-C (mA)</td>
<td>150</td>
</tr>
<tr>
<td>Discharge gap (µm)</td>
<td>300</td>
</tr>
<tr>
<td>Scanning speed (µm/s)</td>
<td>5</td>
</tr>
</tbody>
</table>
3.3.1. The Experiments of Arc Trajectory

The arcs with machining angles of 90° and 180° are used to verify whether the deposition method can process the arc trajectory. The diameter of circular arc is 0.5 mm, and the number of trajectory scanning is 20. The experimental results are shown in Figure 15.

![Figure 15](image_url)

**Figure 15.** Example of HV-μEAM metal layer (a) trajectory deposition effect of 90°, (b) trajectory deposition effect of 180°, (c) and (d) are the photos of depositions observed by Ultra Depth of Field 3D Microsystem.

It can be seen from Figure 14 that the deposited layers are dense and evenly distributed, and the deposition profiles are clear, and the heights are 99.74 and 114.85 µm, respectively. It is proven that this method can be used to process arc trajectories at different angles.

3.3.2. The Experiments of Complex Trajectory

The deposition method can be used for processing straight lines and arc-shaped tracks. In order to verify the deposition effect of the straight line and the arc-shaped connection, a complex deposition track experiment is designed. The machining trajectory is shown in Figure 16, which is composed of the English letters ‘QD’. The scanning trajectory of the first layer is: A→A→B→C→B, the scanning trajectory of the second layer is: B→C→B→A→A. The number of trajectory scans is 20, the processing time is about 2.5 h. The deposition effect is shown in Figure 17.

It can be seen from Figure 16 that the deposition effect of the complex trajectory obtained by this method is ideal, the deposition layer is dense and uniform, the deposition outline is clear, the deposition height is 139.09 µm. It is proven that the selection of the experimental parameters is reasonable, and it is also proven that the machining method of high voltage induced weak arc discharge deposition can be used to process the complex trajectory.
Figure 16. Diagram of scanning trajectory.

Figure 17. Example of HV-µEAM metal layer of ‘QD’ letter (a) metal layer in the scope of 3 mm × 2 mm in X-Y plane and 139.09 µm in height using 200 µm electrode and (b) the photo of metal layer of ‘QD’ letter observed by Ultra Depth of Field 3D Microsystem.

4. Conclusions

In this paper, a new metal deposition method on monocrystalline silicon wafer surface by HV-µEAM is proposed. Metal deposition in large discharge gap can be realized by the interaction of HV and RM-V. The different discharge processes of HV discharge alone and HV-µEAM were analyzed. The influence of various process parameters on the deposition effect were studied, and the optimized process parameters were given. The feasibility of this method is further verified by the deposition experiments of complex trajectories.

- The discharge processes of HV single discharge and HV-µEAM were studied, and the feasibility of HV-µEAM was verified.
- The experiment of HV-µEAM single point on monocrystalline silicon wafer surface was carried out. The effects of various process parameters on the experiment were studied. The optimal process parameters were obtained as follows: RM-V 110 V, RM-C 150 mA, discharge gap 300 µm, scanning speed 5 µm/s.
- Deposition processing of complex trajectory was carried out. The deposition is dense and continuous, the outline is clear and the height is 139.09 µm. The junction between the straight line and the circular arc can achieve a better transition, which proves that this deposition method can achieve the deposition processing of complex tracks on monocrystalline silicon wafer and provides a new choice for realizing the patterning of metallic materials.

Funding: This work was financially supported by the National Science Foundation of China (Grant Nos. 51875300, 51871128), Shandong Provincial Natural Science Foundation, China (Grant Nos. ZR2017MEM012, ZR2018MEM017). Partial supported by Key research and development plan of Shandong Province (Grant Nos. 2018GGX103036, 2018GGX103022).

Conflicts of Interest: The authors declare no conflict of interest.

References

7. Hou, Y.; Huang, Z.; Gao, Y.; Ge, Y.; Wu, J.; Chu, J. Characterization of Mn$_{1.56}$Co$_{0.96}$Ni$_{0.48}$O$_4$ films for infrared detection. Appl. Phys. Lett. 2008, 92, 202115. [CrossRef]


© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).