IMPROVING PERFORMANCE IN MICROMACHINING OF SILICON WAFER USING HEAT-ASSISTED MICRO ELECTRICAL DISCHARGE METHOD

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

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FEBRUARY 2022

DEDICATION

Dedicated specially to My beloved parents **Daud bin Jusoh & Wan Zaharah binti Wan Mahmood, my siblings and Families, Ahmad Dzulhazril bin Daud, Noor Dzuliana binti Daud, Ahmad Dzulhairi bin Daud, Ahmad Dzulhakim bin Daud, Nurul Ameera binti Md Kamar, Mohd Redwan bin Mustapha, Anis Afiqah binti Mohd Azmi**, **Nursyafawati binti Abd Samad** and **All my supportive friends** for their support, prayer and encouragement throughout my PhD life.

ACKNOWLEDGEMENT

First and foremost, “Syukur Alhamdulillah” to Allah, the Most Gracious and Most Merciful for ensuring myself to be healthy to carry out my study and to complete this thesis.

Secondly, I would like to express my warmest gratitude to my supportive supervisor, Assoc. Prof. Ir. Dr. Mohamed Sultan and Assoc. Prof. Ir. Dr. Leow Pei Ling who have provided immeasurable support and guidance toward the completion of my thesis. Their remarkable ideas and suggestions will be much appreciated in the future.

My sincere appreciation also goes to my family especially my parents Daud Jusoh and Wan Zaharah and my siblings who have been so tolerant and supportive in all years either morally or financially. Thanks for their continuous encouragement, love and emotional supports that they had given to me all this while to complete this thesis.

I would like to gratefully thanks to all my colleagues, Izni, Aalia, Akmal, Shahida, Farah, Aqilah, Hasan, Marwan, Alaa, Omer, Amri, Anis and Ifah, who had given me helps technically and mentally throughout my journey in completing my thesis. Thanks a lot from the bottom of my heart. I wish you all the best in life and hope that our friendship will never last forever

Thank You and Wassalam.

ABSTRACT

Microelectrical discharge machining (μEDM) is a non-traditional machining technique that has high potential in the processing of semiconductor materials. This technique can produce complex three-dimensional (3D) shapes without cutting forces, to eliminate the tendency of crack propagation, due to the localized pressure on the workpiece. Additionally, it can also produce high precision and good surface quality machining results. However, this method has only been used to machine highly conductive materials such as metals and highly doped silicon (Si) wafers. While this method is not suitable for undoped or lightly doped Si wafers, increasing the conductivity of the Si wafers requires an additional process and cost. This work aims to investigate the μEDM performance for machining highly and lightly doped *n*-type Si wafers with various electrical conductivities. The machining performance was examined on both high- (1-10 Ω.cm) and low- (0.001-0.005 Ω.cm) resistivity Si wafers by means of a range of discharge energies (DE). The results revealed that the parameters of the electrical resistivity and DE of the μEDM have a great influence on the Si wafer machining performance, in terms of machining time, material removal rate (MRR), surface quality, surface roughness (SR), and material mapping. The minimum amount of DE required to machine the Si wafer was 5μJ for both low and high-resistivity Si, of which the highest MRR of 5.842×10^{-5} mm^3/s was observed for the low-resistivity Si. On the contrary, the best SR, R_a, of 0.6203 μm was achieved for high-resistivity Si, indicating a higher carbon percentage after the machining process. A novel machining method called heat-assisted μEDM, which increases the conductivity of the lightly doped Si wafer prior to the machining, was used. A *p*-type Si wafer was tested, and the machining performance was observed while varying the temperature values of the Si wafers in the range of 30 – 250 ^{0}C. The results indicated that increasing the machining temperature contributes to a higher MRR, lower tool wear rate and lower SR. MRR of 1.43×10^{-5} mm^3/s and a SR of 1.487 μm were achieved at 250 °C. This study is expected to promote the advancement of microelectromechanical systems devices in the electronics field, as well as the ability to achieve a high aspect ratio machining with high surface quality results.

ABSTRAK

Pemesinan nyahcas mikro-elekrik (µEDM) adalah satu teknik pemesinan tidak tradisional yang mempunyai potensi yang tinggi dalam pemprosesan bahan semikonduktor. Teknik ini boleh menghasilkan bentuk 3-dimensi (3D) kompleks, tanpa daya pemotong, bagi mengelakkan kecenderungan retak disebabkan tekanan ke atas bahan kerja. Tambahan pula, ia boleh menghasilkan keputusan pemesinan yang berketepatan tinggi dan mempunyai kualiti permukaan yang baik. Namun begitu, kaedah ini digunakan dalam pemesinan bahan berkonduktif tinggi seperti logam dan silicon (Si) wafer berkonduktif tinggi. Namun, kaedah ini tidak sesuai bagi Si wafer tidak berkonduktif atau berkonduktif rendah, peningkatan kekonduksian memerlukan proses tambahan dan kos. Dalam kajian ini, penyiasatan prestasi µEDM sebagai alat untuk memesin Si wafer yang berkonduktif tinggi dan rendah dengan nilai kekonduksian berbeza dikaji. Prestasi pemesinan dikaji bagi kedua-dua Si wafer jenis-*n* berintangan tinggi (1-10 Ω.cm) dan rendah (0.001-0.005 Ω.cm), dengan mengunakan tenaga nyahcas (DE) dalam julat tertentu. Keputusan kajian ini mendedahkan bahawa parameter rintangan elektrikal dan DE dari µEDM mempunyai pengaruh besar terhadap prestasi pemesinan Si wafer, dari segi masa pemesinan, kadar penyingkiran bahan (MRR), kualiti permukaan, kekasaran permukaan (SR) dan pemetaan bahan. DE yang diperlukan untuk memesin kedua-dua Si wafer berintangan rendah dan tinggi adalah 5 µJ, dengan MRR tertinggi 5.842 x 10^{-5} mm^3/s, dicatat oleh Si berintangan rendah. Sebaliknya, SR terbaik, R_a bernilai 0.6203 µm, dicapai oleh Si berintangan tinggi, dan peratusan karbon yang tinggi ditunjukkan selepas ia dimesin. Salah satu teknik pemesinan baru dinamakan bantuan haba µEDM, dapat meningkatkan kekonduksian Si berintangan sederhana, sebelum dimesin. Si wafer jenis-*p* telah diuji dalam kajian ini, dan prestasi pemesinan dinilai, sementara nilai suhu Si wafer dibezakan dalam julat 30–250 °C. Keputusan menunjukkan peningkatan suhu menghasilkan MRR yang tinggi, kadar penggunaan alat yang rendah dan SR yang rendah. MRR bernilai 1.43×10^{-5} mm^3/s dan SR bernilai 1.487 µm dicapai pada suhu 250 °C. Kajian ini dijangka dapat mempromosi sistem bahan mikroelektronik dalam bidang elektronik, dan berupaya mencapai keputusan pemesinan pada nisbah yang tinggi dengan kualiti permukaan yang baik.

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LIST OF ABBREVIATIONS

3D - Three-dimensional
μEDM - Microelectrical discharge machining
2D - Two-dimensional
CNC - Computer numerical control
DE - Discharge energy
EBM - Electron beam machining
EDM - Electrical discharge machining
EDX - Energy-dispersive X-ray
FESEM - Field emission scanning electron microscope
FIB - Focused ion beam
IBM - Ion beam milling
IC - Integrated circuit
LBM - Laser beam machining
MEMS - Microelectromechanical Systems
MRR - Material removal rate
NC - Numerical control
SD - Sintered diamond
SEM - Scanning electron microscope
Si - Silicon
SR - Surface roughness
TEM - Transmission electron microscope
TWR - Tool wear rate
USM - Ultrasonic machining
UV - Ultraviolet
VPSEM - Variable pressure scanning electron microscope
WEDG - Wire electrical discharge grinding
Wire-EDM - Wire electrical discharge machining

LIST OF SYMBOLS

μ - Micro

f - Frequency

S - Static stress on tool

H_0 - Surface fracture strength

R - Radius

Y - Vibration amplitude

$S(\theta)$ - Yield

D - Density

C_l - Constants depend on material & conversion efficiency

L_p - Laser power

E_v - Vaporization energy

F_l - Focal length

α - Beam divergence

w - thickness

I - Current

T_m - Melting point

Rs - Sheet resistance

π - Pi

V - Voltage

Ω - Ohm

ρ - Electrical resistivity

σ - Electrical conductivity

s - Equally space probes

T - Temperature

K_t - Thermal conductivity

C_p - Specific Heat capacity

q_w - Heat flux

q_o - Maximum heat flux

R_s - Spark radius

T_s	-	Temperature of workpiece adjacent to cavity boundary
T_0	-	Ambient temperature
h	-	Convective heat transfer coefficient
t_d	-	Pulse duration
η	-	Proportion of DE per pulse
E	-	DE per pulse
C	-	Capacitance
q_a	-	Convective heat flux
h_a	-	Temperature-dependent for derive convective heat transfer coefficient
V_a	-	Rate of generate cavity
H	-	Latent heat of melting

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CHAPTER 1

INTRODUCTION

1.1 Overview

Micromachining has become an essential tool for the fabrication of miniature sensors, actuators and microsystems. It has also been used to fabricate three-dimensional (3D) microstructures and is the foundation of a technology called Microelectromechanical Systems (MEMS). Micromachining technology provides great flexibility and low cost in the case of the mass production of silicon (Si) for MEMS applications [1]. Since MEMS technology has encouraged the progress of semiconductor integrated circuit (IC) design, it has drawn significant attention to use Si as one of the essential elements in the manufacturing process. The significant investment in Si IC has led to the advancement of material structure technology on a scale of less than a micrometer. Basic processing steps of IC manufacturing technology involve thin film deposition, doping and lithography, micromachining techniques including special deposition, etching and bonding processes that allow for the formation of three-dimensional micro-structures.

Traditional MEMS fabrication methods based on chemical etchings use two-dimensional (2D) photolithography for the processing of Si bulk MEMS Systems. The chemical etching has been proven to be efficient in the formation of 2D structures. However, it is not applicable to form 3D structures. This is due to its dependency on crystal orientations and line-of-sight etching. Non-traditional machining techniques such as ultrasonic machining, ion beam milling, laser machining and electrical discharge machining (EDM) have been developed to address these limitations.

1.2 Problem Statement

Existing conventional Si machining techniques are commonly based on a photolithography process and chemical etching which lacks the ability to form complex 3D geometries. This is due to its dependency on crystal orientation and line of sight etching [2]. The increasing commercial interest toward microsystems demands for complex Si 3D structures. To meet these rising demands, non-traditional micromachining techniques such as laser and EDM have been explored. Theoretically, these techniques can produce Si structures of any suitable form. However, various practical issues such as cracks and thermal damage are associated with these techniques. EDM is among the proven machining methods that produce high precision and good surface quality 3D structures, but it can only be used for machining conductive material. This is because the material removal process starts with electro-thermal action with repeated electrical discharges occurring between the tool and workpiece. EDM is a thermal machining method with non-contact force, and is ideal for machining hard and brittle semiconductors such as Si [3]. Over the past few years, many researchers have reported the machining of the Si wafer with EDM, but the Si wafers had to be doped and coated with conductive material such as gold [4], nickel [5], and aluminum [6] to make them machinable. The machining performance showed promising results, but the additional process involved would have an effect on the material properties. This work proposes a heat-assisted microelectrical discharge machining (µEDM) method, without the need for a coated layer. The effect of the temperature would alter the electrical conductivity of the Si wafer to be machined by µEDM.

1.3 Research Objectives

The main objectives of this research are to machine lightly doped Si wafers using a new machining technique of heat-assisted μEDM. The specific objectives are as follows:

(a) To evaluate the effect of temperature on the electrical resistivity of lightly doped Si wafers.

(b) To find the optimal machining parameter for die-sinking μEDM technique with different Si resistivity.

(c) To develop a heat-assisted μEDM method for machining lightly doped Si wafers.

(d) To analyze the μEDM performance, including the material removal rate (MRR), tool wear rate (TWR), surface quality and the material property.

1.4 Scope of Study

The scope of this research focuses on the development of a μEDM technique for machining highly and lightly doped Si wafers. The machining process involved two techniques, which are the die-sinking μEDM and the proposed heat-assisted μEDM. The materials used for the die-sinking μEDM are highly and lightly doped Si wafers of n-type and p-type to characterize the effect of the electrical resistivity to the μEDM Si machining. The proposed heat-assisted machining covered temperature ranges from 30 to 250 °C to heat the Si wafers in order to be machined by the μEDM by reducing its resistivity during machining. The measurement of the Si wafer resistivity was performed using a four-point probe method setup to analyze the resistivity value of Si wafers that are machined by μEDM. The machining performance of Si wafers using μEDM were analyzed and characterized based on MRR, TWR, surface quality and surface characterization. In addition, using COMSOL Multiphysics Finite Element Analysis tool, validation of MRR at various temperatures was performed and compared with the experimental data.

1.5 Significance of Study

The rapid growth of micro and nano fabrication technologies has driven MEMS sensors and actuators to be utilized in various fields such as robotics, automotive, biomedical and portable electronic devices. These applications have successfully fabricated micro-scale measurement devices that were once an impossible challenge. Additionally, MEMS have provided benefits in 3D micromachining structures, which makes the fabrication processes of MEMS devices crucial. The µEDM is among the micromachining techniques used to fabricate MEMS devices, which enables fast and precise 3D structure formation in the Si wafers. However, it is only effective on the surface of the material that is conductive. This research aims to enhance the functionality of the µEDM by developing improved machining capabilities in a heat-assisted technique to temporarily increase the electrical conductivity of Si during µEDM, without affecting the Si properties. Moreover, the blower fan was used to remove debris in order to generate stable machining rather than using vibrations, which also limits the possibility of bending the electrode during machining. Meanwhile, this method has salient implications in the machining field of micro and nanotechnology research for various applications. In addition, the develop machining method is expected to improve machining efficiency, without permanently changing the electrical and mechanical properties of Si.

1.6 Thesis Outline

This study focuses on the micromachining of lightly doped Si wafers using heat-assisted µEDM, and the impact of temperature variations on the electrical conductivity of Si. This thesis consists of six chapters. Chapter 1 contains a brief overview of the micromachining process, as well as their applications in the MEMS system. This chapter also discusses the problem statement, objectives, scope and significance of the study.

Chapter 2 discusses the literature review undertaken, which includes types of non-traditional micromachining techniques such as ultrasonic machining, ion-beam machining, laser beam machining and EDM on Si wafers. The characteristics and fundamentals of each of the micromachining techniques are discussed in relation to the types, material removal process performance, and reviews of previous work on the machining of Si wafers. The last section discusses the contrast of the characteristics of these four machining techniques.

Chapter 3 presents the research methodology, as well as the workflow and simulation of the MRR results that have been used to validate the experimental results. The Si wafer micromachining experiments are divided into two categories, namely, a die-sinking µEDM and heat-assisted µEDM. A brief explanation of the experimental work and the measurement of the electrical resistivity of Si wafers using a four-point probe method are also presented in this chapter.

Chapter 4 reports the experimental works of the machining of Si wafers with various resistivity levels by die-sinking µEDM that operates by means of various ranges of discharge energy (DE). The chapter starts with the experimental setup and the parameters used to evaluate the effects on the machining performance. Finally, the findings of this investigation, along with the analysis data, are presented and characterized.

Chapter 5 proposes a novel heat-assisted µEDM that operates by means of temperature variation during machining. The chapter starts with measurements of the resistivity of Si wafers, followed by the experimental setup of the heat-assisted µEDM. Next, the experimental findings and analysis data based on the machining performance are discussed and characterized accordingly.

Finally, the thesis concludes with Chapter 6, wherein the key results are recapped and some worthy directions for future work are presented, followed by a list of publications arising from the thesis.

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