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碩 士 論 文

超快雷射薄石英晶圓微鑽孔研究

Research on Micro-drilling of Thin Quartz Wafer Using Ultrashort Pulsed Laser

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中文摘要

石英晶體擁有比陶瓷、鎳鉻合金更優異的化學穩定性，因此被廣泛投入在半導體、光機電等科技行業的儀器和設備上，自 1880 年居里兄弟(Curie)發現壓電效應後，眾多自然界或人工合成的壓電材料逐漸被挖掘出來，20 世紀中期以 α-quartz 單晶石英為載體的振盪器開始大量使用於電子網絡系統，作為時脈訊號產生的核心，AT-cut 切向的單晶石英具有良好的頻率穩定性，是該類被動、主動元件運用的大宗。到了 21 世紀，從 4G、5G 資訊網絡，到工業機電系統，太空衛星也包含在通訊循環的體系中，每年需製造 200 億顆以上的電子元件供應需求，並對數位訊號的穩定性有更上一層的要求。除此之外，為符合商業需求，過去幾十年裡，半導體相關行業都在追求更精細的尺寸、更低的成本和更快的速度，開發新興技術或持續精進原有成熟製程勢在必行，如何快速薄石英晶圓上鑽出微米級的孔洞，用以佈線、蒸鍍金屬電極連接內部振盪晶圓和增加晶體運行得穩定性，為一項極具前景的研究。

石英晶體的硬脆和高穿透特性讓其在精密加工領域具備一定的挑戰性，超快雷射因其具備低熱影響、高加工速度和低材料耗損率，被視為極有前景的加工方式之一，本研究使用波長 1030 nm 及 515 nm 之振鏡飛秒雷射系統，探討雷射光束特性及掃描策略對於厚度 80 μm 石英晶圓鑽孔的影響，並配合氫氧化鉀(KOH，35 wt.%)蝕刻後處理，實驗結果證實相較於 1030 nm 的 P 偏振紅外雷射，515 nm 之 S 偏振綠光雷射能夠精準將圓孔內部的材料去除或改質，並成功於 3.6 s 和 2.5 s 內完成直徑 70 和 50 μm 的微孔加工，TEM 檢測的結果亦表明 KOH 蝕刻的成效十分優異，孔洞內無多晶、非晶區的存在，實現錐度最佳可小於 1°之高品質通孔，參數優化後可期媲美旋切、貝索光束等先進製程，降低生產成本。

關鍵字: 石英、飛秒雷射、雷射輔助濕式蝕刻微鑽孔、偏極化效應、孵化效應

Abstract

Quartz crystals possess superior chemical stability compared to ceramics and nickel-chromium alloys, making them widely used in instruments and equipment in industries such as semiconductors and optomechanics. Since the discovery of the piezoelectric effect by the Curie brothers in 1880, numerous naturally occurring or artificially synthesized piezoelectric materials have been gradually unearthed. In the mid-20th century, oscillators using α-quartz single-crystal quartz as a carrier began to be extensively used in electronic network systems as the core for generating clock signals. AT-cut quartz crystals exhibit excellent frequency stability and are widely utilized in passive and active components.

In the 21st century, from 4G and 5G information networks to industrial electromechanical systems and even space satellites, all encompassed in the communication infrastructure, the demand for manufacturing over 20 billion electronic components annually has grown. Therefore, there is a higher requirement for the stability of digital signals. In addition, to meet commercial needs, the semiconductor industry and related sectors have been pursuing more precise dimensions, lower costs, and faster speeds over the past few decades, which necessitates the development of new technologies or the continuous improvement of existing mature processes. The rapid drilling of micrometer-sized holes on thin quartz wafers for wiring, metal electrode deposition, internal oscillator wafer connections, and improved crystal stability is a highly promising research area.

The hardness and brittleness of quartz crystals, as well as their high penetration characteristics, have posed significant challenges in the field of precision machining. Ultrashort pulsed lasers, due to their low thermal impact, high processing speed, and low material consumption rate, are considered one of the promising methods for machining quartz. In this study, a femtosecond laser galvanometer system with wavelengths of 1030 nm and 515 nm was used to investigate the influence of laser beam properties and scanning strategies on drilling holes in 80 μm thick quartz wafers. The experiment was combined with post-processing using a 35 wt.% potassium hydroxide (KOH) etching solution to remove the residual recast layer after laser processing.

The experimental results confirmed that the 515 nm S-polarized green laser, compared to the 1030 nm P-polarized infrared laser, can precisely remove or modify the material inside the holes. Micro-drilling with diameters of 70 μm and 50 μm was successfully completed within 3.6 s and 2.5 s, respectively. Transmission electron microscopy (TEM) analysis also indicated excellent performance of KOH etching, as no polycrystalline or amorphous regions were observed inside the holes. This achieved high-quality through-holes with a taper angle of less than 1°, and with parameter optimization, the process can be expected to be comparable to advanced techniques such as trepanning optics system and Bessel beam, thereby reducing production costs.

Keywords: quartz, femtosecond laser, laser assisted wet etching micro-hole drilling, polarization effect, incubation effect