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論　文　内　容　の　要　旨

氏　名　（　高 悦　）	
論文題名	Highly reliable Cu particles sinter joining for die−attach of next generation power devices （次世代パワーデバイスに向け高信頼性銅粒子ペースト接合技術の開発）

論文内容の要旨

Next generation power devices based on wide gap band (WBG) semiconductor materials, such as SiC, GaN, GaO, diamond and soon, have attract much attention because their excellent endurance performance for high working temperature, high current density, high voltage and high operating frequency. In order to realize the promising performance of WBG devices, the assembly and package technology of these chips in devices are also crucial. Among of that, the die-attach materials, which directly bond the WBG chips to substrates, largely determine the servicing performance and long-term reliability of these power devices. The die-attach materials with high operating temperature, high conductivity and high reliability are required in these WBG devices. Metallic particle pastes are considered as the most suitable solution, especially, copper (Cu) particles paste has attracted intensive attention due to its high temperature stability and excellent conductivity with reasonable cost. However, to achieved high reliable sintered Cu joint, high sintering temperature, high assisting pressure and reductive gas protection are necessary. Those complicated sintering condition limited the wide application of Cu sinter joining. Thus, this work aims to achieve highly reliable sintered Cu joints in a relative mild sintering condition. The main topics of this thesis including the improvement in Cu particle synthesis, modification in Cu paste fabrication, and evaluation of the reliability

At first, a simple and large-scale polyol method was utilized to synthesize bimodal Cu particles under air atmosphere. The size, size distribution, and morphology of Cu particles were controlled by the reaction parameters, such as Cu source and additives. Insoluble Cu source was certified to be suitable for the formation of bimodal Cu particles. The insoluble Cu source provided a slow and steady Cu ions supplement for the formation of fresh Cu nuclei. And then the fresh Cu nuclei continuously modified the nucleation and growth of the following Cu particles. In addition, sodium sulfide (Na_2S) additive had also controlled the size of Cu particles due to its reduction capability, which accelerated the formation of Cu particles. These results indicate that the Cu source and additives can optimize the particles size and size distribution in the polyol process and open a new way for the formation of metallic particles. However, in this part, the good bonding strength was only achieved in formic acid atmosphere which was not suitable for industrial application.

To endow the Cu paste with the sinterability even at inert atmosphere, reductant additive were added into Cu paste. The shear test results show that the ascorbic acid (AA) as reductant additive could realize the steady sintered Cu joints at 300 °C with inert N_2 protection. AA could endow the Cu paste with self-reduction and self-protection characteristics. The self-reduction characteristic is due to the reduction process of AA, as it reduces the Cu oxide layer on the metal Cu even at room temperature. The self-protection characteristic is due to the decomposition of AA, which prevents further oxidation during the sintering process. These characteristics are beneficial for the sintering of Cu particles and for enhancing the bonding strength of joints. High shear strength of 27.8 MPa were achieved by the improved Cu paste.

The next step was reliability evaluation of sintered Cu joints, Thermal storage test was performance on the sintered Cu joints. In both high temperature storage test and high humidity test, the sintered Cu joints shows good stability in shear strength. However, the Cu oxides was also observed in the aged Cu joints. Those Cu oxides was proved to contribute to the bonding performance. The thermal shock reliability of sintered Cu joints on SiC power device application was also investigated. Silicon carbide (SiC) dummy chips were bonded to DBC substrate and thermal shock test from -40 °C to 250 °C were performed both in the ambient atmosphere and in vacuum. Then, the SiC MOSFETs bonded by sintered Cu joints were evaluated by power cycle test from 25 °C to 200 °C and the thermal conductivity was evaluated by T3ster equipment. The results showed the sintered Cu exhibited extremely high reliability during the thermal shock aging test in ambient atmosphere although inferior reliability was observed in vacuum. This phenomenon was investigated and explained. And the power cycle test showed no obvious deterioration occurred, which proved the good reliability of sintered Cu joints.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

SiC等のワイドバンドギャップ（WBG）パワー半導体を用いたパワーデバイスの普及には、WBGダイを基板に高性能・高信頼性に接合するダイアタッチ技術の開発が欠かせない。銅（Cu）焼結接合技術は、優れた電気・熱特性と高温安定性だけでなく、低コストを実現する技術として注目を集めている。しかしながら、Cu焼結接合では、高い焼結温度、高加圧、更に、還元性ガス保護が必要になり、これらの複雑な焼結条件がCu焼結接合の広い応用を制限している。本論文では、独自の粒子合成から溶媒の調整を経て新たなCu焼結接合技術を開発し、実装プロセスの低温化、低加圧化、窒素雰囲気化を実現し、更にその信頼性の評価を実施している。その結果は、以下の様に得られている。

1. ポリオール法を用い、プロセスパラメータの調整によりワンポットで 2 つの粒子サイズ（バイモーダル）分布を持つ Cu 粒子の合成を達成している。Cu 粒子合成における Cu 源および添加剤と反応パラメータの制御により、得られる粒子径分布を制御することが出来る。バイモーダル Cu 粒子は均一 Cu 粒子より優れた接合性能を示すことを明らかにしている。
2. 窒素雰囲気の焼結接合を実現するため、焼結時に還元力を発現する添加剤を混合した Cu 焼結ペーストを提案している。還元剤としてアスコルビン酸（AA）の微量添加により、300℃、0.4 MPa、窒素雰囲気の条件で、27.8MPaの高強度接合が実現できることを示している。
3. 250℃までの大気中高温放置試験、および、85℃/85RH%の高湿度試験において、ダイアタッチ構造で Cu 焼結接合層の酸化が進行するが、ダイ接合の剪断強度は増加を示す。SiC ダイを DBC 基板にダイアタッチした構造を用いた−40℃～250℃の熱衝撃試験、SiC MOSFET を用いた 200℃までのパワーサイクル試験によって信頼性を評価し、いずれも高い信頼性の保持が可能なことを示している。

このように、本研究では新たなCu粒子焼結接合材料の合成方法を確立し、還元力を付与するペースト化応用展開を明示し、更に、新規ペーストを用いたデバイス実装構造を作製し信頼性について詳細な評価を行い、Cu粒子焼結接合が、次世代パワー半導体のダイアタッチ材料として優れた特性を有することを示している。

よって本論文は、博士論文として価値あるものと認める。