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Ultrasound assisted nickel plating and silicide contact formation for vertical multi-junction solar cells

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Abstract

Vertical multijunction (VMJ) silicon solar cells (SC) are considered the most preferred among all known single-crystal ones for using in various photovoltaic systems under conditions of highly concentrated sunlight. The techniques of ultrasound assisted nickel plating (USNiP) of mirror polished silicon wafers and their subsequent vacuum annealing for VMJ SC ohmic contacts creating were tested by X-ray diffractometry, scanning electron microscopy and dark current–voltage characteristics. The feasibility of utilizing nickel electroplating in the sulfamate electrolyte for the NiSi ohmic contact made on the mirror polished silicon wafers with n^{+}–p junctions on both sides have been experimentally confirmed. Ultrasound assistance of the nickel plating insured the enhancement of NiSi adhesion and improving the quality of the ohmic contacts.

Keywords: Vertical multi-junction solar cells; Electroplating; Nickel monosilicide; Ultrasound

1. Introduction

According to Razykov et al. (2011), in terms of technology, crystalline and polycrystalline silicon wafers (c-Si and pc-Si, respectively) are the main materials for the world photovoltaic (PV) industry. At the present, over 80% of the world PV industry is based on c-Si and pc-Si wafer technologies. Concentrator photovoltaic is considered to be a promising technology in terms of the cost of generated electricity. Among other, the vertical multijunction solar cell (VMJ SC) or edge illuminated SC has good potential applications in high concentration photovoltaic (Xing et al., 2013). Silicon high-voltage VMJ SC produced by stacking multiple wafers followed by orthogonal cutting possess several inherent advantages over conventional photovoltaic SC (Sater, 2003; Rafat, 2006; Pozner et al., 2011; Simakin et al., 2008). According to Sater and Sater (2002), high-voltage VMJ SC have shown a capability to accept high concentrations of up to 2500 suns, with peak efficiency of about 20% (see also Vasil'ev and Tyukhov, 1995). Pozner et al. (2011) mentioned that high-voltage SC with low series resistance can be good candidates for concentrating PV systems, which are usually constrained by high currents leading to high losses related to series resistance, as well as the small-area VMJ SC can also be good choice include different solar-powered stand-alone photovoltaic/thermal (PV/T) systems (Simakin et al., 2008). The low manufacturing costs, the well-established technology of silicon together with the advanced methods of cutting and sizing

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can lead to VMJ SC playing a significant role in the competition of different types SC (Rafat, 2006).

The bonding of the silicon wafers with vertical *p–n* junctions for the creation of VMJ SC are usually performed by metallization of both n^+–Si and/or p^+–Si sides of the Si plates by nickel films and by their subsequent flux wetting and dipping compressed stack of the metallized wafers in molten tin-lead solder (Strebkov and Poljakov, 2010). Feature is that the surfaces of the silicon wafer subjected to nickel plating must be mirror polished, which complicates the adhesion of nickel to silicon. Commonly, a contact metallization of silicon wafers performed through a step of electroless nickel (Chaudhari and Solanki, 2010; Kim et al., 2005; Sabharwal et al., 2008; Boulord et al., 2009; Tous et al., 2012). However, these authors observed a poor adhesion of electroless Ni film to Si and proposed some additional steps for their improvement. Namely, Boulord et al. (2009) suggested texturizing of Si surface using a chemical etching in a KOH solution. Chaudhari and Solanki (2010), as such as Kim et al. (2005) and Sabharwal et al. (2008) used activation step in $PdCl_2$ solution before Si metallization and subsequent annealing of the Ni layers in an inert atmosphere of N_2 or Ar between temperatures ranging from 350 to 500 °C to obtain a highly conductive nickel monosilicide NiSi in order to achieve adhesion of electroless nickel with silicon and to create ohmic contact. Radical way for the improving adhesion of the metallization is applying of the seed layers of the noble metals Au, Pd, Pt, Ag, and their compositions with Ti, In, Co etc. (Chaudhari and Solanki, 2010; Kim et al., 2005; Boulord et al., 2009). We have previously suggested (Klochko et al., 2013) the conditions of the bonding of silicon VMJ solar cells with *p–n* junctions using Ag–In solder, obtained by electrochemical deposition of good adhesion Ag and In films on Si surface. Unfortunately, the high cost of precious metals are contrary tendencies of a reducing the cost of SC. As claimed by Beaucarne et al. (2012), the strong long-term increase of the price of silver in combination with the falling wafer costs has led to a situation where metallization evidently dominates wafer-to-cell conversion costs. As a result, the industry has set out an aggressive roadmap concerning metallization, targeting strongly reduced silver consumption and higher performance. According to Kim et al. (2005), despite the fact that the evaporated Ti/Pd/Ag contacts have been widely used for high-efficiency cells used in space, those metals are too expensive to be applied for terrestrial applications. Furthermore, the evaporation process is not applicable to mass production because a high vacuum is needed. Among other non-precious metals Ni film deposition onto Si has advantages, because the formation of NiSi at the interface between silicon and nickel enhances stability and reduces the contact resistance, has low resistivity, low formation temperature (350–750 °C), and low film stress. So, nickel-plating and the nickel monosilicide prepared by annealing according to (Chi et al., 2007; Tous et al., 2012) must replace the conventional silicides $TiSi_2$ and $CoSi_2$, and therefore the search for the alternative methods for successful Ni deposition onto mirror polished surfaces continues.

As such as electrochemical microfabrication offers some unique advantages over competing technologies and therefore finds increasing applications in the electronics and microsystems industries (Datta and Landolt, 2000), nickel electrodeposition may be a promising way to create ohmic contacts between the highly doped silicon wafers in the VMJ SC. According to Llona et al. (2006), these substrates conduct sufficiently well to allow plating using a peripheral electrical contact on the wafer. As reported Datta and Landolt (2000), electrochemical microfabrication technology is expected to play an increasingly important role in the electronics and microsystems industry because of its cost effectiveness and achievable high precision. In addition, electrochemical processes are attractive from an environmental point of view because material deposition or removal is highly selective thus minimizing waste. To improve Ni adhesion to the silicon, authors (Llona et al., 2006) have been electroplated 2 μm thick Ni films using a nickel sulfamate bath on both n^+- and p^+-type silicon wafers. In order to provide adhesion series of trenches with different widths had been previously etched in the wafers by a plasma etching. However, such patterning of the silicon wafers with the creation of 7 μm deep trenches for the ensuring of adhesion is unacceptable for the silicon wafers of VMJ SC with the depth of the $p–n^+$ junctions less than 2 μm. Llona et al. (2006) also note that there is another problem associated with hydrophobic Si surfaces obtained after removing the native oxide layers by the using, for example, hydrofluoric acid (HF) solutions. These surfaces are indeed conducting sufficiently, but repelling water and water based solutions such as the nickel sulfamate electrolyte that can be a problem has to be resolved for successful plating of the wafers.

Our investigations concerning electrodeposition of some metals under unsteady plating modes (Klochko et al., 2014) have revealed that ultrasonic agitation of the electrolyte during plating improves adhesion of metals to the different substrates and helps to ensure a smoother metallization. The effects of ultrasound on the electrochemical deposition processes have been the topic of the several recent studies. Jensen et al. (2003) have shown that ultrasonic streaming can provide the uniformity of Ni electroplating; namely, filling characteristics on three-dimensional patterned brass cathode geometry with millimeter-sized features were improved considerably. Moreover, the topography of the Ni-deposit is evidently influenced by the use of ultrasound. Awad et al. (2007), who investigated nickel plating on Si_3N_4/Si substrates with Ag-seed layers have revealed that the use of ultrasonic bath resulted in a considerable decrease of grain size and in a reduction in deposit porosity, so, by using ultrasonic bath much smoother nickel films free from voids or defects were achieved.

Therefore, we decided to test the capabilities of ultrasonic electrolyte mixing during nickel plating for the improvement of the Ni coatings characteristics and to