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THE WAFFLE: A NEW PHOTOVOLTAIC DIODE GEOMETRY HAVING HIGH EFFICIENCY AND BACKSIDE CONTACTS

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ABSTRACT

By employing anisotropic etching techniques and advanced device processing it is possible to micromachine new types of mechanical, electronic, and optical devices of silicon, which have unique properties. In this paper the characteristics of a new type of photovoltaic diode fabricated employing these processing techniques are described. This novel device has not only high efficiency, but also has both contacts placed on the backside of the cell. The first devices which are only 50 mm in diameter are of relatively good quality with low leakage currents (nA), high breakdown voltages (80V), and low series resistance (mohms). The measured efficiencies at AM 1.5 lie between 12 to 15 % with short circuit currents of 25 - 30 mA/cm2, and open circuit voltages of 0.58 - 0.6 V.

INTRODUCTION

In the manufacture of photovoltaic diode panels it is necessary to connect a number of devices in series in order to obtain the correct operating voltage.For standard panels the number of cells required is most often 36. For the case of single crystal and multicrystalline silicon cell panels the devices are connected by soldering or welding a thin metal foil from the front side of one cell to the backside of the neighboring cell, continuing in this fashion until all cells are connected in series. This is at best a difficult task and a completely satisfactory automated process for this step the manufacture of silicon solar cell panels has not been devised. Were it possible to place both contacts to the diode on the backside of the device the task of interconnection would be simplified considerably and made more amenable to automated execution. Some attempts have been made to do this, e.g. the multijunction solar and the Polka Dot cell (1,2,3), but they have not been completely successful.

By employing some of the new techniques devised for the fabrication of silicon microsensors and micromechanical devices, new types of electronic, and optical, as well as, mechanical devices can made that are unique. In this paper application of these silicon, "micromachining" , processes to the fabrication of a new type of photovoltaic diode with both contacts on the backside is described. The task of connecting the cells in series during the panel fabrication step is, thus, facilitated. As a matter of fact it should be possible to automate the whole process relatively easily by printing all interconnects on a supporting substrate and simply soldering all cells down on this. The name of this photovoltaic diode arises from the fact that the front side of the device actually looks like a ,"waffle". The structure which is achieved by anisotropic etching of {100} single crystal silicon through a photolithographically generated mask makes it possible to bring the front contact to the back of the cell and, furthermore, results in a corrugated front side with a reduced reflectivity and no metal contacts which reduce the area exposed to the sun. First, some design considerations are discussed, thereafter fabrication is taken up.

DESIGN CONSIDERATIONS

The geometry of the device is shown in Figure 1. It is immediately clear what has been done to place both contacts to the diode on the backside. By employing the micromachining techniques mentioned above holes having an inverted pyramid - like structure are etched into the {100} oriented silicon wafer. By photolithography and diffusion it is then possible to fabricate the structure shown. In addition to permitting both contacts to be placed on the backside of the diode this, "waffle", structure has a number of advantages. First, the active surface area compared with a normal cell is increased by approximately 2 times. Secondly, the average reflectance of the surface is reduced by the inverted pyramid structures, thus, improving the absorption of light. Next, since there are no metal contacts on the front surface, shadowing effects are reduced, again improving the absorption of light. Finally, since the waffle geometry reduces the volume of the cell, the collection efficiency of the electrons and holes genrated, in particular at longer wavelengths, is improved.

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FABRICATION

For the fabrication of the devices made for this study {100} oriented 10 ohm cm silicon wafers were used. Because of the deeply etched inverted pyamid structures, great care must be excercised in the fabrication since many of the processes are not compatible with the etching process. The first step is to etch the inverted pyramidsin a 30 % solution of potassium hydroxide (KOH) in water at a temperature of 80 °C, leaving an approximately 25 μm thick membrane. Thereafter, the relatively deep boron and phosphorous contact diffusions are made at a temperature of 1150 °C. Next, the waffle is etched again this time leaving a thin membrane, the thickness of which is determined by the "etch-stop" action of the backside boron contact diffusion. Finally, the frontside boron diffusion is made, completing the device. The resultant structure is shown in the SEM microphotograph reproduced in Figure 2. There is a compromise involved in this last diffusion in that one would like to have a very shallow junction, but not so shallow as to increase the series resistance of the cell too much. A view of the front and back side of two finished devices is shown in Figure 3. The design does not make optimum use of the silicon area available but the advantageses of this geometry are evident.

ELECTRICAL AND OPTICAL MEASURMENTS

The first measurements taken on the finished devices were their electrical characteristics. The breakdown voltage (BV) of the diodes were measured to be 80 ± 10 V. Series resistance (R_s) values between 10 - 100 mohms were measured indicating considerable variation in the junction depths of the p diffusions. Groove and stain measurements, though not very precise, confirm these results. Leakage currents I_l in the

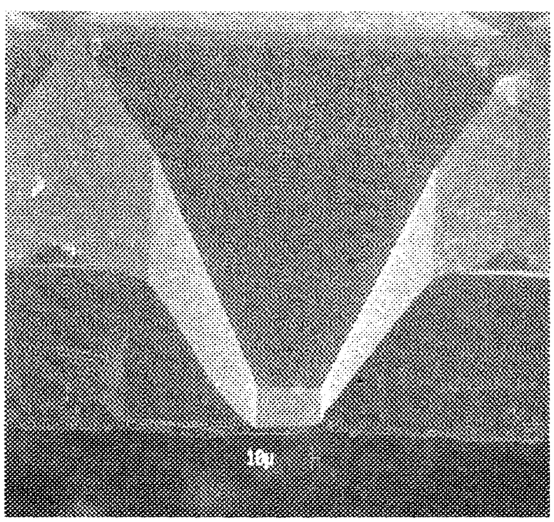

Figure 2. Seen here is a SEM picture of a Waffle photodiode cleaved in such a manner as to show the cross section of the device.

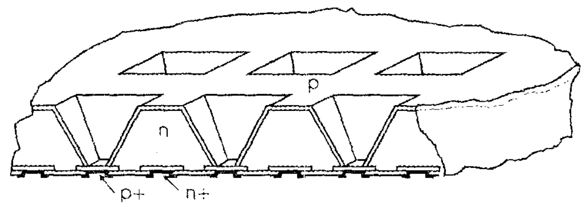

Figure 1. A sketch of a cross section of the Waffle photovoltaic diode showing the geometry. An indication of scale can be given by noting that both the wafer thickness of the devices and the distance between contacts is 300 um.

nanoampere range and minority carrier lifetimes (τ_{rec} and τ_{diff}) of 10 - 50 μsec, determined from current - voltage measurements, indicate reasonbly good control over the process and good quality material. The current - voltage characteristics shown in Figure 4. show an open circuit voltage of 0.58 V and a short circuit current of about 30 mA/cm^2 at AM 1. 5, indicating a power efficiency of roughly 13 %.

CONCLUSIONS

A new single crystal silicon photovoltaic diode structure has been demonstrated that not only has relatively high efficiency (12 - 15 %), but also has both contacts on the backside of the device, thus, permitting simplified interconnection. This is not the only geometry that one could use for an efficient photovoltaic diode, but it is clear from this work that many attractive solar cell structures can be made employing advanced silicon micromachining techniques. However, it must be admitted that fabrication of these devices requires very advanced and complicated processing and the question arises as to whether or not photovoltaic diodes produced by these methods will ever be economically viable.

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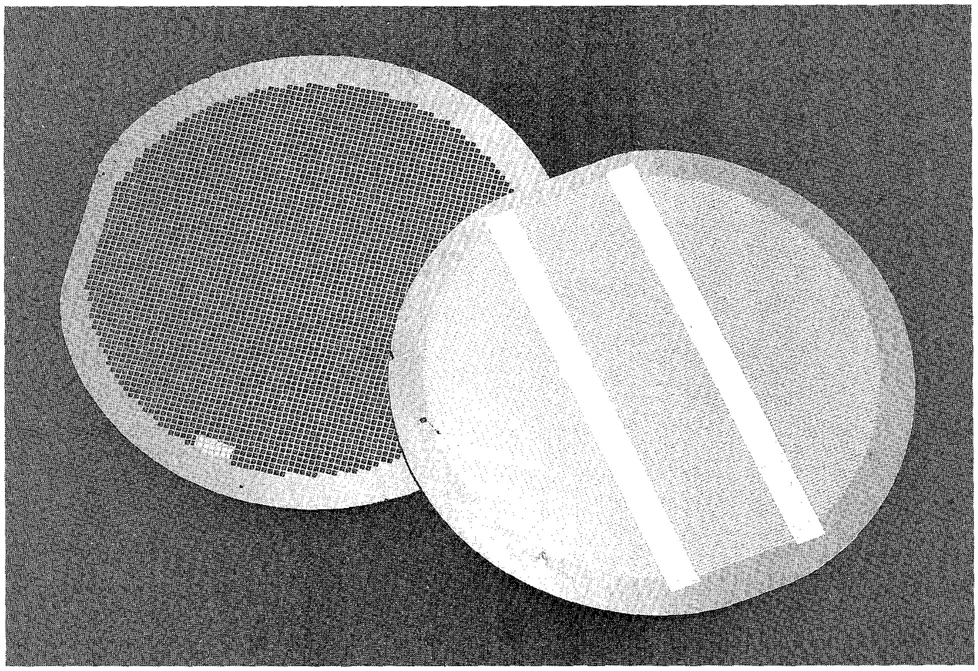

Figure 3. A photograph of two Waffle photodiodes showing the front and back geometries. Note how black the inverted pyramid geometry of the frontside appears.

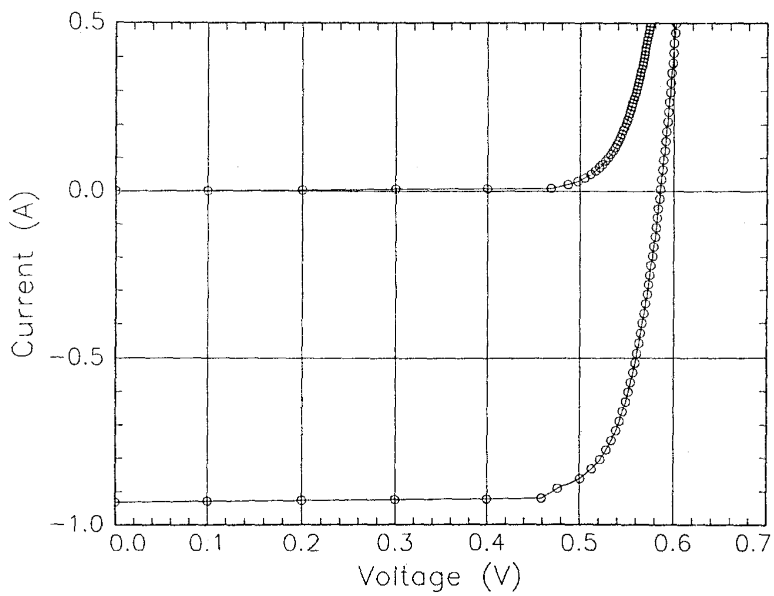

Figure 4. The current - voltage characteristics of the diodes were recorded on a HP 4145B Transistor Parameter Analyser. The device shown here has an efficiency of approximately 13% based on an estimated effective area of 30 cm^2 and a fill factor of about 0.75.