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THE ALUMINUM P-SILICON SCHOTTKY BARRIER·········ITS BARRIER HEIGHT AND SPECTRAL RESPONSE UNDER LOW IRRADIANCE

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Abstract—*Schottky barriers are formed by deposition of thin aluminum film onto p-silicon wafer with a very thin interfacial layer of natural oxide. The barrier height has been measured to be arrouud 0.80 v, which is substautially greater than the formerly reported value by other investigators. This is believed due to the thin interfacial layer of oxide saturates the dangling bonds on the semiconductor surface and results in a less density of surface states.*

The spectral response of the shallow surface barrier under low irradiance is studied with a monochromatic light source from wavelength 0.4 μ to 0.9 μ. The measued result, which is quite different from that of a conventional p-n junction photovoltaic cell, shows no diminution in the infrared region, and a quantum efficiency higher than 75% is obatained.

1. INTRODUCTION

Schottky-barrier diode has the advantages of low turn-on voltage and fast speed. Its shallow barrier is also very attractive in the application for photo devices, although antireflection coating must be considered.

A high barrier height means less reverse saturation current in rectifying and larger open-circuit voltage in photo application[1]. Aluminum *p*-silicon Shottky barrier has been reported to have a barrier height of 0.58 *v*, which is substancially less than the theoretical limit of 0.92 *v* predicted by simple Shottky relationship. In this investigation special care is exercised to avoid heating the metal-semiconductor contact during the fabrication process. A very thin layer of natural oxide on the chemically etched silicon surface serves as a protection from aluminum penetration, and it also saturates the dangling bonds on the silion surface. In this way a barrier height of much closer value to the theoretical limit can be achieved.

2. BARRIER FORMATION AND HEIGHT MEASUREMENT

when a metal is making intimate contact with a semiconductor, at thermal equilibrium a double layer of opposite charges will be created to line up the Fermi levels in the two materials. The double layer forms a potential barrier which is responsable for the rectifying property of a Schottky barrier. The barrier heights of metal-semiconductor contacts are, in general, determined by both the metal work function and the surface states.

By the analogy with the equation for metal on *n*-type semiconductor, given by Cowley and Sze[2], the barrier height ϕ_B for metal on *p*-type semiconductor can be expressed in the form[3]

$$\phi_B \simeq \gamma(\chi_S - \phi_M + \phi_g) + (1-\gamma)\phi_o \qquad (1)$$

where χ_S is the electron affinity the semiconductor, ϕ_M the work function of the metal, ϕ_g the energy gap of the semiconducto, and ϕ_o the neutral level for surface states measured from the top of the valence band. The neutral level specifies the level below which all surface states must have been filled for charge neutrality at the surface. The constant γ is defined by $\gamma=\epsilon_i/(\epsilon_i+q^2\sigma D_S)$, where σ and ϵ_i are the thickness and permittivity of the interfacial layer respectively, q the electronic charge, ane D_S the density of surface states per electron-volt per unit area of the semiconductor surface. If there are no surface states, then $\gamma=1$ and Eq. (1) reduce to the simple Schottky relationship $\phi_B=\phi_g-(\phi_M-\chi s)$.

For aluminum *p*-silicon contact

$\phi_g=1.12\,v$
$\phi_M=4.25\,v$
$\chi_S=4.05\,v$

a value of $\phi_B \simeq 0.92\,v$ is expected.

On the other hand, if D_S is very large ($>10^{14}\ cm^{-2}ev^{-1}$) γ tends towards zero and $\phi_B \simeq \phi_o$, *i. e.* the barrier is independent of ϕ_M but pinned by the neutral level which is approximately one third of the energy gap for silicon. For a moderate amount of surface-state density, ϕ_B is expected to be in a value between 0.33 and 0.92 *v*.

p-type silicon wafers of <111> orientation ranging in resistivity of 1.13 to 28 *Ω cm*, corresponding to a concentration of 5×10^{14} to $10^{16}\ cm^{-3}$ are used in this investigation. The wafers are first cleaned and chemically etched before the evaporation of aluminum in a veacuum of 10^{-6} torr. An aluminum film 5,000Å in thickness is deposited onto the back side of the wafer and sintered to form ohmic contact. The front side is then submitted to evaporation of thin aluminum film dots of 200Å in thickness with the pattern defined by a metal mask. The diameter for each aluminum dot is 0.198 *cm*. The thickness of the film is monitored by a quartz oscillator thickness monitor during evaporation, and measured by a interferometer afterwards. To get a good Schottky-barrier contact the evaporation source is kept away far enough from the substrate to prevent the aluminum from reacting with the thin natural oxide and penetrating thrugh it.

The barrier height is first measured by the photoelectric method. The measurement is made with a Bausch and Lomb grating monochromator (No. 33-86-03). The result is shown in Fig. 1 where the extrapolation shows a barrier heigt of 0.796 *v*.

The forward current-voltage characteristics is also used to find the barrier height. From the result of Fig. 2, for an effective Richardson constant of $A^*=79.2$ $Amp/cm^2/^oK^{2}$[4], and area $A=3.08\times10^{-2}\ cm^2$, the barrier height is calculated to be 0.802 *v* fairly agreed with that measured by photoelectric method, and a surface-state densisty $D_S \simeq 3\times10^{12}\ cm^{-2}ev^{-1}$ is estimated.

Finally the differential capacitance measurement is made with a Booton 74*D* capacitance bridge at test frequency of 100 *KHz*. In Fig. 3 the solid line shows the result of the measurement. From the intercept on the voltage axis, $\phi_B=0.99\,v$ is estimate. The much higher apparent barrier height can be invoked to the image force lowering, the effects of surface states, and the interfacial layer with electric field[5]. Under relatively higher reverse bias conditions, the metal area far from the bonding point is less reverse biased than those near the bonding point due to the unavoidable voltage drop produced by the leakage current. The net effect is a capacitance

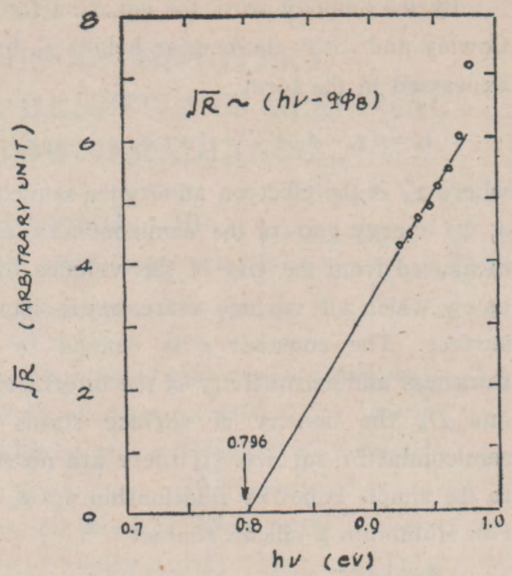

Fig. 1 Square root of photoresponse versus photo energy.

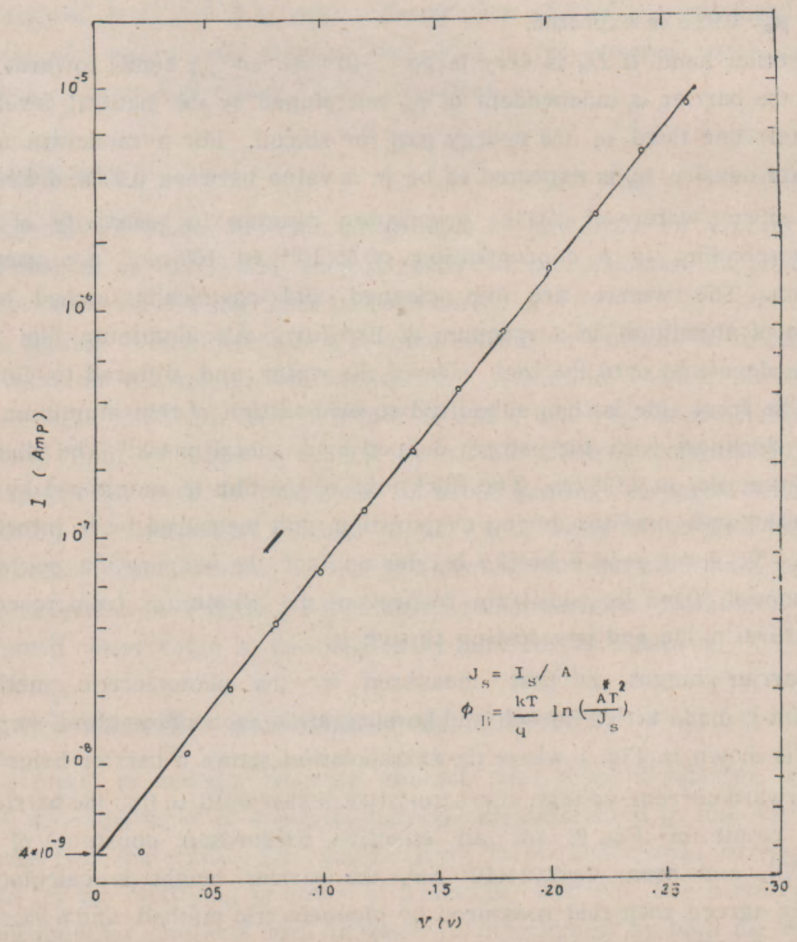

Fig. 2. Forward current versus voltage

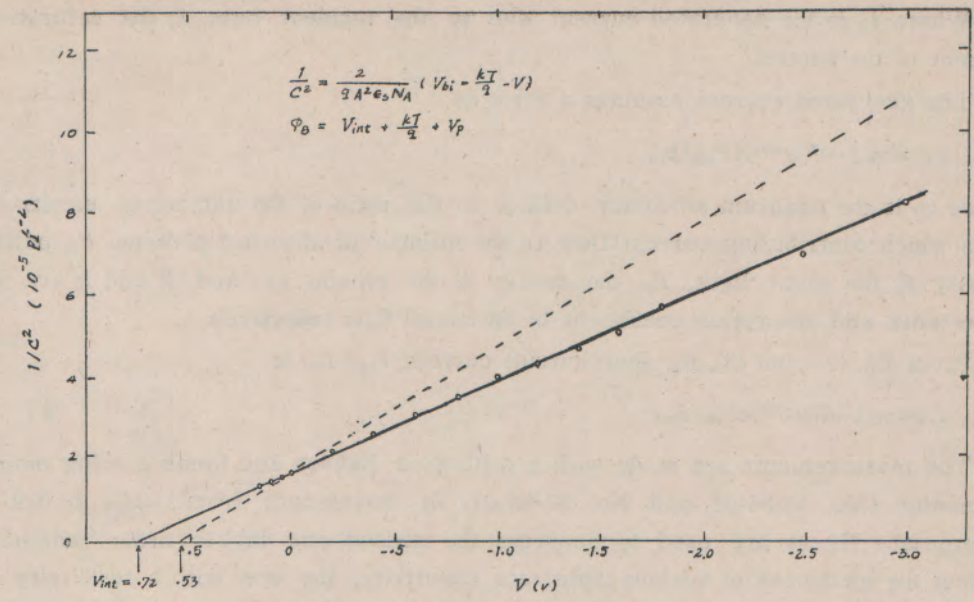

Fig. 3. $1/C^2$ versus applied voltage

which changes less rapidly with voltage then expected. Since there is no voltage drop in the absence of applied bias, the zero-bias capacitance should by quite accurate. Hence the slope of the measured straight line is lower and apparent barrier height is larger than the true value. For an estimate of the electrically effective area, the slope of a dashed line in Fig. 3 by joining the proper intercept 0.53 v, which corresponds to the 0.80 v barrier height, and the zero-bias capacitance point is measured and an effective area of 93% is obtained.

The measured value of barrier height, 0.80 v, is substantially greater than 0.58 v of aluminum p-silicon barrier obtained by Smith et al[3]. It is certainly a success in increasing the barrier height toward the theoretical limit of 0.92 v. This is believed to be due to the relaxation of dangling donds of the atoms on the semiconductor surface by an interfacial layer of silicon dioxide and thus results in a much lower surface-state density. The fact that the interfacial layer is transparent to the charge carriers can be seen from the near-ideal forward characteristics obtained in current-voltage measurement, where the exponent $n=1.36$.

3. SPECTRAL RESPONSE UNDER LOW IRARDIANCE

When light comes upon the metal-semiconductor contact the absorber photons may create electron-hole pairs in or near the depletion region. The electron-hole pairs either in the depletion region of diffused into it from within a diffusion length will be separated by the potential barrier and are capable of delivering electrical power to an external load.

Under low irradiance the effect of the series resistance can be neglected, and the current-voltage characteristics of such a Schottky barrier is given by

$$I=I_s(e^{qV/nkT}-1)-I_L \tag{2}$$

Where I_L is the generated current due to the incident light, I_s the saturation current of the barrier.

The generated current assumes a form as

$$I_L = \eta_q(1-R)e^{-\alpha t}AP_{in}/E_{tp} \tag{3}$$

where η_q ir the quantum efficiency defined as the ratio of the number of electtron-pairs which contributing current flow to the number of absorbed photons, P_{in} power density of the input light, E_{ph} the energy of the photon ev, and R and α are the reflectance and absorption coefficient of the metal film respctively.

From Eq. (2), and (3), the short circuit current $I_{sc}=I_L$. or

$$I_{sc}=\eta_q(1-R)e^{-\alpha t}AP_{in}/E_{ph} \tag{4}$$

The measurements are made with a calibrated Bausch and Lomb grating monochromator (No. 33-86-02 and No. 33-86-03) in wavelength from $\lambda=0.4$ to 0.9 μ. Appropriate filters are used to suppress the second and higher order radiation. Among the specimens of various substrate resistivity, the one with a resistivity of 28Ωcm corresponding to a doping concentration of 5×10^{14} cm^{-3} shows a larger output. This may be due to the degradation of the output of the specimens with lower resistivity by larger series resistance other than that introduced by the substrate material, whereas for a substrate with larger resistivity the depletion width and diffusion length of minority carrier are greater. The measurements performed hereafter is the results of the specimen with the substaate resistivity of 28 Ωcm. The measured spectral response of the barrier is shown in Fig. 4. The short-circuit current (solid line) increases with wavelength, showiog no diminution in the infrared region. This is quite different from that of a conventional p-n junction silicon solar cell (dashed line), of which the spectral response reaches a maximum at the vicinity of 0.75 μ and then decrease with increasing wavelength very rapidly.[6] This can be invoked to a decreasing of reflectance at the aluminum film[7] in this range of wavelength.

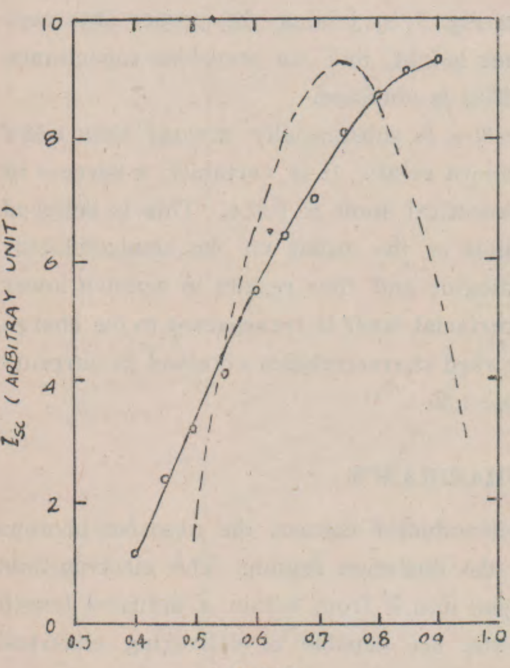

Fig. 4. Spectral response of aluminum p-silicon (solid line) compared with that of a conventional p-n junction solar cell (dashed line).

The short-circuit current vs. input power density at different wavelength is shown in Fig. 5. From Eq. (4) the quantum efficiency can be obtained as

$$\eta_q=[E_{th}/A(1-R)e^{-\alpha t}]\frac{dI_{sc}}{dP_{in}}$$

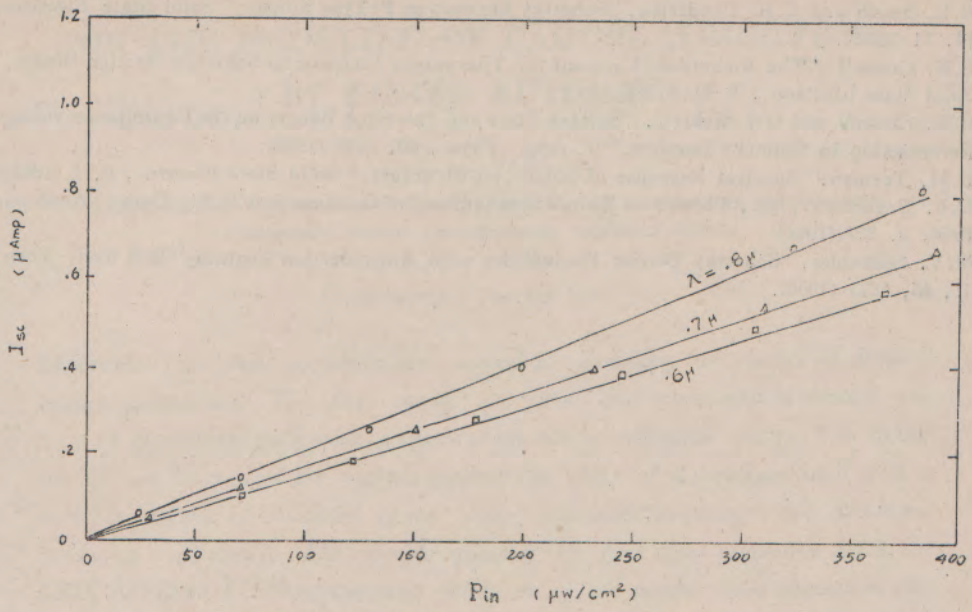

Fig. 5. Short-circuit Current versus Input Power Density

Although the line of the longer wavelength shows a larger slope the quantum efficiency, on the contrary, is less than that of a shorter wavelength because of frequency dependence of the reflectance. Using the proper reflectance[7] and assuming no absorption in the metal film, an estimated value of quantum efficiency higher than 75% is obtained. High quantum efficiency of Schottky-barrier photodiode has also been achieved by other workers.[8] This is because the penetration depth of light in silicon is very short demanding a barrier very closs to the surface, which is a condition satisfied best for a Schottky-barrier diode.

4. CONCLUSION

A Schottky barrier with near-ideal characteristics has been made by evaporation of thin aluminum onto p-type silicon. The barrier height has been increased to a value of 0.80 v by permitting an inlerfacial layer of natural oxide on the surface of silicon. Further experimental investigation on the effect of the thin oxide layer on barrier height and current-voltage characteristics of other metal-semiconductor contacts is suggested.

The spectral response which does not dimish at the infrared region is certainly supperior to that of a conventional slicon p-n junction photovoltaic cell in sensitivity when it operates in that region. The high quantum efficiency suggests the possibility of application for radiation detection at low irradiance.

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