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J.F. Verwey, W. Ruis, I. Sens. Charge transport in oxygen-doped polysilicon layers on Si. *Revue de Physique Appliquée*, 1978, 13 (12), pp.821-824. 10.1051/rphysap:019780013012082100 . jpa-00244553

HAL Id: jpa-00244553

<https://hal.science/jpa-00244553>

Submitted on 1 Jan 1978

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PASSIVATION.

CHARGE TRANSPORT IN OXYGEN-DOPED POLYSILICON LAYERS ON Si

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Résumé. — On montre que les couches minces de silicium polycristallin dopé avec de l'oxygène (polydop) peuvent être utilisées pour la passivation des jonctions p-n au-dessous des couches. Le mécanisme de la conduction est dérivé des mesures dans les couches minces déposées directement sur les cristaux de silicium. A la température ambiante on trouve une conduction Poole-Frenkel et à une température plus haute on a probablement une conduction par les sauts d'un piège localisé à l'autre.

Abstract. — It is shown that layers of polysilicon doped with oxygen (polydop) can be used for the passivation of underlying p-n junctions. The conduction mechanism was derived from measurements in layers directly deposited on to silicon crystals. At room temperature we found Poole-Frenkel conduction changing at higher temperatures, presumably, to hopping in localized states.

1. How can polydop passivate p-n junctions ? —

Semi-insulating polysilicon (SIPOS) has been suggested for the passivation of p-n junctions in silicon. Layers of polycrystalline silicon were made semi-insulating by adding oxygen during growth [2]. We studied these layers grown at a reduced pressure. We call them polydop which stands for polysilicon doped with oxygen.

Figures 1 and 2 are used to demonstrate how polydop layers can passivate underlying p-n junctions. Figure 1 shows a cross-section of a p-n junction near the Si-SiO₂ interface. If positive charge is present in the SiO₂ (indicated by crosses) then the depletion layer of the junction is constricted at the interface. Consequently, the breakdown voltage of the junction is lowered.

In figure 2 a slightly conducting layer of polydop is present between the charged oxide and the silicon crystal. In this case the charge in the oxide induces negative charge in the polydop layer and no constriction of the depletion layer takes place. So, the breakdown voltage of the underlying junction becomes insensitive to the amount of oxide charge. Then the

FIG. 1. — Cross-section of a p⁺-n junction covered by a charged SiO₂ layer.

FIG. 2. — Cross-section of a p⁺-n junction with polydop between oxide and silicon.

junction is passivated for oxide charge and also for external fields, which have the same effect as a charge.

The influence of external fields on the breakdown voltage was studied in gated diodes. The result is shown in figure 3. The polydop layer was grown at a pressure of 0.5 torr from a stream of SiH₄ and N₂O at a temperature of 650 °C. The layer with a thickness of 0.5 μm was coated with a 0.9 μm SiO₂ layer by chemical vapour deposition. Figure 3 shows (curve 1) the breakdown voltage V_{BV} as a function of the voltage V_g applied to an Al electrode (gate) on top of the SiO₂ layer above the place where the p-n junction intersects the Si-polydop interface. Curve 2 shows V_{BV} of an identical junction without polydop. In the former case no effect of V_g can be seen, hence it can be concluded that good passivation against external fields is obtained.

For the passivation effect it is necessary to have polydop layers that are slightly conducting in order to induce variable amounts of charge in them. Therefore we studied the conduction in more detail.

FIG. 3. — Breakdown voltage V_{BV} as a function of the gate voltage V_g of gated diodes with (curve 1) and without (curve 2) properly working polydiox.

2. Conduction mechanism. — The conduction of the polydiox layers was measured in the structure of figure 4. Usually this quantity is measured in layers on top of a relatively thick SiO_2 layer in a direction parallel to the surface of the silicon crystal [2, 3]. In our approach the conduction was measured in layers directly deposited onto the Si-crystal, as can be seen in figure 4. This structure is better related to the use of polydiox in practical devices where it is also directly deposited onto the silicon. The central Al dot in figure 4 has a diameter of $570 \mu\text{m}$, the outer Al stripe is used for the reduction of the surface leakage current.

Figure 5 shows an example of current-voltage curves obtained in polydiox layers. The current depends on the polarity of the voltage. The current indicated by F in figure 5 is obtained with forward polarity. In this case the metal electrode on the polydiox layer is positively biased with respect to an n-type substrate (or negatively biased with respect to a p-type substrate). The R in figure 5 indicates reverse bias, i.e. the opposite polarity. In this case a positive voltage on the metal electrode induces a depletion layer in a p-type substrate and a substantial voltage drop takes place across it. In this way, the reverse current is smaller than the forward current.

FIG. 4. — Cross-section of the structure used for conduction measurements of the polydiox layers.

FIG. 5. — Current-voltage curves of a polydiox layer. Curve F is the forward current (accumulation in Si). Curve R is the reverse current (depletion in Si).

In polydiox layers on highly doped substrates (n^+ -type) the forward and reverse currents are equal. Presumably, the charge carriers are then able to tunnel through the relatively thin depletion layer in the reverse current mode. Therefore, we conclude that the forward current is governed by processes in the bulk of the polydiox. We studied the forward current in more detail in order to obtain information on the conduction mechanism in the polydiox.

Figure 6 shows the forward current I_F as a function of voltage V_F in a double-logarithmic plot. In this figure we plotted two curves, one for *excess current* and the other for *typical current*. The excess current behaviour was measured in less than 5 per cent of the samples. Therefore, we may conclude that the excess current behaviour is due to residual inhomogeneities in the polydiox layers. If the polydiox layers were grown at atmospheric pressure then the excess current behaviour was dominant. The typical current behaviour in figure 6 is ascribed to the intrinsic conduction in *homogeneous* polydiox and this is further analysed.

At relatively low fields the forward currents showed an ohmic region from which the resistivity can be calculated. At higher fields the current became non-ohmic which is likely to be due to Poole-Frenkel conduction (see for instance ref. [4]). In this conduction mechanism the current is given by

$$I_F \sim \exp \beta' \left(\frac{V_F}{d} \right)^{1/2} \quad (1)$$

FIG. 6. — Forward current as function of the voltage of two samples on one wafer.

where d is the thickness of the layer, β' is the Poole-Frenkel constant,

$$\beta' = \left(\frac{q}{2\pi\epsilon} \right)^{1/2} \cdot (kT)^{-1},$$

q is the elementary charge, ϵ is the permittivity, k is Boltzmann's constant and T is the temperature.

FIG. 7. — Poole-Frenkel plot of the forward current in polydiox layers with different thicknesses.

FIG. 8. — Poole-Frenkel plot of the forward current in polydiox layers with different oxygen concentrations.

FIG. 9. — Forward current in polydiox layers as function of the voltage for different temperatures.

Figure 7 shows a Poole-Frenkel plot of the forward current in polydiox layers with different thicknesses. One may observe that straight lines are obtained except for the thinnest layer. Presumably this layer is not sufficiently homogeneous. The results in figure 7 support a model of Poole-Frenkel conduction.

Figure 8 shows Poole-Frenkel plots for the forward current in layers with different oxygen concentrations. Again reasonably straight lines were obtained with a slope that was not very much dependent on oxygen concentration. From the value of the slopes we calculated a value for ε that was between that of

silicon and silicon dioxide. We found a relative dielectric constant of about 7 which may be compared with 3.9 and 11.7 for SiO_2 and Si respectively.

Figure 9 shows the forward current for different temperatures. The curve for room temperature (295 K) was a straight line in a Poole-Frenkel plot but the curves for higher temperatures were not. Apparently they have a simple exponential relation with the applied voltage V_F . Possibly, the voltage dependence must now be explained by hopping from one centre to the other (Ref. [3]). These centres are likely to be localized states in the forbidden band of the silicon (Ref. [3]).

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