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p-type emitters covered with a thin CdS layer show a substantial improvement of V_{oc} and FF

Karl W. Böer *

Department of Physics and Astronomy, University of Delaware, Newark, DE 19736, USA

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ABSTRACT

A number of p-type emitters of solar cells, covered with a thin, copper-doped CdS layer, show a significant increase in open circuit voltage and fill factor. This is caused by field limitation in the junction to 50 kV/cm, and induced by field quenching in photo-conducting CdS. As a result, the junction field increases when the bias is reduced from forward toward V_{oc}; however, it cannot increase above the critical field for the onset of field quenching. Consequently, electron leakage through the junction interface is reduced, which could otherwise occur in uncoated solar cells when the junction field approaches tunneling fields. In addition, with increasing quenching the Fermi level moves further away from the conduction band, causing the bands at the junction interface to disconnect. As a consequence of field quenching, the CdS enters a range of negative differential conductivity, creating a high-field domain that absorbs increased voltage in the reverse bias range without increasing the junction field. The doping density with Cu is critical; it is self-adjusted by limited solubility of Cu in CdS and is extremely difficult to realize homogeneously for any other known semiconductor cover layer.

1. Introduction

It is well known that a layer of CdS of only a few 100 Å in thickness is sufficient to increase the solar conversion efficiency of CdS/CdTe and CdS/CIS solar cells [1–9]. Here CIS can be the original copper–indium diselenide or any of many other similar type of cells, where In is alloyed with Ga or other homologous elements of Se are used to substitute. In CdS/CdTe, which is the best researched, the improvement in V_{oc} typically (depending of treatment) exceeds 50% and that of the FF exceeds 15% [6].

This fact is known for almost three decades, and many researchers have tried to replace CdS with any other binary or higher compounds, however, with no marked success. The question before us is two-fold: what is the reason that CdS causes such a marked improvement of efficiency, and why is it that CdS and no other compound can perform a similar task.

We will in the bulk of this presentation try to answer both questions and will, for this purpose, prepare the discussion by analyzing a typical *pn*-junction behavior since it is suggestive of the junction with CdS responsible for the effect. However, even though the actual solar cell is polycrystalline and topographically non-planar, we have chosen a simple one-dimensional model to present the principles involved. Also, it is well known that the characteristics of the cell depend substantially on the treatment and we do not attempt with the presented explanation to explain quantitatively these rather complex results. We will also not include the discussion of the back contact of CdS, since there are not enough details available, and it is not relevant to the CdS behavior near the junction interface.

Since there is a large body of undisputable evidence available for single crystal CdS platelets, we will refer to these results when they appear to be applicable to the CdS-part of the junction [11–18].

1.1. Typical pn-junction behavior

The CdS-part of the junction can be approximated as a Schottky barrier, and its carrier density, space charge, potential and field distribution are described by the transport and Poisson equation. A typical behavior is shown in Fig. 1 for increasing bias as a family parameter [11,12].

It is suggestive that the lowest applied voltage, shown in Fig. 1 represents substantial forward bias. The barrier (as well as the junction) is flattened, there is little voltage drop across and the maximal field is below 10 kV/cm for a barrier with a defect density of 10^{17} cm^{-3} (as a reasonable density in a recrystallized CdS layer). With increased voltage drop (moving toward open circuit condition) the barrier widens in CdS and the maximum field increases rapidly (this should not be confused with the capacity behavior of the entire junction, which is substantial in CdTe). With a change in bias of only 0.4 V, the maximum field in CdS increases to100 kV/cm.

* Tel.: +1 610 388 0560; fax: +1 610 388 1356
E-mail address: solpax@aol.com

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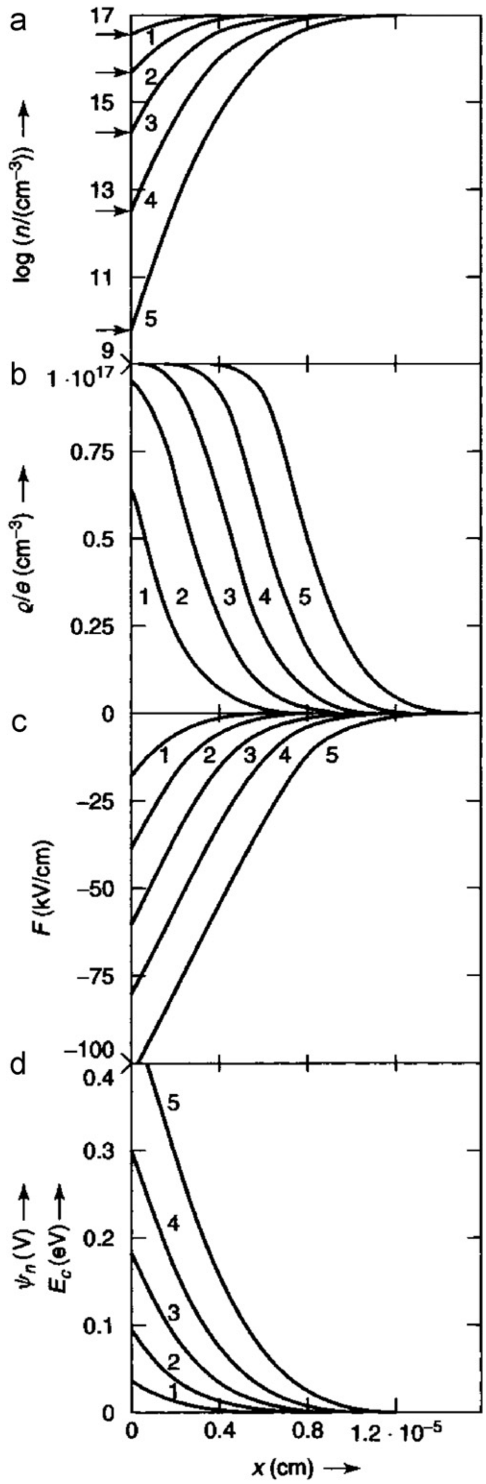

Fig. 1. Carrier density, space charge, field and potential energy (band-edge) distribution (a–d) of a typical Schottky barrier to a blocking contact on the left, shown as an example. It is evident that with higher bias (curves 1–5 shown in subfigure (d)) the space charge region in the junction is widened (subfigure (b)) and consequently the maximum field increases (subfigure (c)). In the given example for a typical space charge density of 10^{17} cm^{-3} it increases from 10 to 100 kV/cm by a changing bias of 0.5 V deduced from a junction model (subfigure (d)).

Obviously, with further increased reverse bias, the maximum field, without limitation, will come close to the tunneling field. This is detrimental for the performance of a solar cell, because of electron leakage across the junction. In the next section we will give a simple mechanism that prevents the field to exceeding roughly 50 kV/cm, and is independent of bias [15].

2. Field quenching in Cu-doped CdS

Cu-doped CdS is *n*-type photoconductive and its electron density can be easily quenched by low energy excitation, e.g., by IR or electric field. Quenching occurs by exciting holes from Coulomb-attractive slow recombination centers into the valence band. From here they can recombine also with fast recombination centers and consequently reduce the photo-excited electron density [13,14]. Field quenching occurs by the Frenkel–Poole excitation [11], i.e., by tilting the bands, thereby easing the thermal escape by lowering the barrier in field direction (see Fig. 2). By a simple estimate of electrostatics one obtains a lowering of barrier of 1 kT for a double ionized Cu^{++} center with an electric field of about $\delta E = 10$ kV/cm [12].

The probability for ionization increases rapidly with increasing electric field and at 40 kV/cm reaches critical values to cause substantial lowering of the conduction electron density due to a substantial field quenching.

2.1. Negative differential conductivity initiated by field quenching

When field quenching increases with increase in applied voltage, the electron density in the conduction band decreases, that is, the conductivity decreases with increase in applied voltage. This causes, for the CdS, a negative slope of the current–voltage characteristics (see Fig. 3a), and hence negative differential conductivity.

When the conductivity decreases steeply than linearly with the field, there are compelling mathematical reasons that the set of transport and Poisson equations can no longer support solutions that describe a homogeneous field distribution. Hence a high-field domain must be formed [14]. Here the field decreases stepwise from a high-field domain near the junction to the low-field region adjacent to the base electrode (dependent on the boundary condition; see Fig. 3b).

The high-field domain is initiated because of field quenching, and starts when the critical field at the junction interface is reached. The field in the high-field domain is then automatically limited to the critical quenching field of ≈ 50 kV/cm. With increasing bias the domain width increases without changing the fields in the high- and low-field regions. This property of high-field domains is

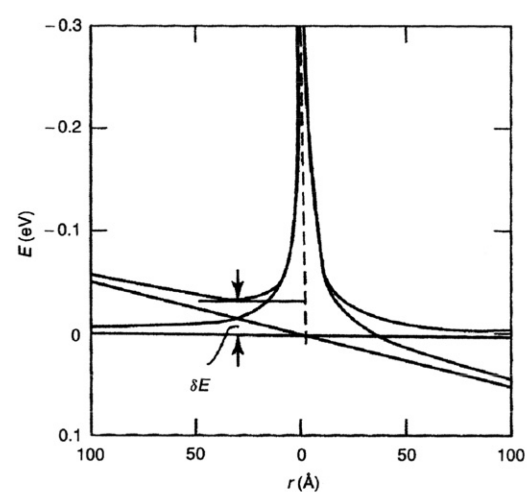

Fig. 2. Potential energy distribution of a Coulomb-attractive hole-trap, shown with and without an acting electric field. The field causes the tilting of the valence band [11].