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Comment on "Mechanisms for the anomalous dependence of carrier lifetime on injection level and photoconductance on light intensity" [J. Appl. Phys. 89, 332 (2001)]

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In a recent article [J. Appl. Phys. 89, 332 (2001)], Karazhanov proposed a single-level recombination model as an explanation for the anomalous dependence of the carrier lifetime on injection-level observed in cast multicrystalline silicon. This approach contrasts with previous models which involved the use of two distinct levels, one causing recombination and the other only trapping. The purpose of this comment is to outline some critical considerations which suggest that only a two-level (or indeed a multi-level) model can satisfactorily explain the experimental observations.

Recently[1], Karazhanov presented an alternative explanation for the very strong injection-level dependence often observed in photoconductance-based lifetime measurements of cast multicrystalline silicon[2], and also other photovoltaic materials[3,4]. This anomalous behavior takes the form of an apparent rapid increase in lifetime as the carrier density decreases below a certain point[2]. He proposed that the phenomenon can be explained by a single set of recombination centers, depending on the energy level and capture cross-sections, and found that the effect is most pronounced when a sample is exactly 'compensated', meaning that the density of recombination centers N_t equals the dopant density N_A.

Previously, the authors of this comment had put forward an explanation for this unusual behavior based on a system involving two energy levels: relatively shallow trapping centers and deeper recombination centers[2]. That work applied theoretical models originally developed in the 1950's by Hornbeck and Haynes[5], and also by Fan[6], to the case of modern solar-grade cast multicrystalline silicon. In this two-level model, the shallow trapping centres do not act as recombination centers, but merely trap and release minority carriers, which nevertheless can cause dramatic changes to the majority carrier density and hence the photoconductance[7]. An important feature of this model is that, in a broad sense, the trapping and recombination effects are 'de-coupled', meaning that it is possible to have varying degrees of trapping and recombination in a given sample. This can not occur in a single-level model.

Karazhanov fitted the single-level model to experimental data published by the current authors[8], and suggested that this model, due to its greater simplicity, was a more satisfactory explanation for the anomalous effect. The purpose of this comment is to point out four key considerations which strongly favor the two-level model (or more generally a multi-level model) as the more satisfactory explanation.

The first point is that the single-level model requires the sample to be 'compensated' for the effect to occur fully. As a result of fitting the model to the experimental data, Karazhanov found that the recombination center density N_t, and therefore the dopant density N_A, in the particular sample modeled should be 4×10^{14}cm^{-3}. However, although unfortunately not mentioned in the article the data was taken from, this *p*-type sample had a resistivity of 0.8Ωcm, corresponding to a dopant density of $N_A=2\times10^{16}$cm^{-3}, in contradiction to the single-level model. As a more general objection, considering that multicrystalline samples always display the anomalous effect to some degree, it seems an unlikely coincidence that compensation would occur in every case.

A second consideration is that, as mentioned above, a single-level system implies a direct correlation between the extent of the anomalous effect and the degree of recombination in any given sample, or, rephrased using the model in Ref. 2, between the trap density N_t and the recombination lifetime. Table I summarizes some values for these parameters from Ref. 2 as measured on four multicrystalline silicon samples, also of resistivity 0.8Ωcm, and shows that there is a distinct lack of correlation. This apparent separation between trapping and recombination was precisely the reason why a two-level system was originally proposed.

The third point supporting a two-level model relates to evidence of this distinction between trapping and recombination centers. Recent studies of trapping centers in multicrystalline silicon[9], in which samples were subjected to thermal annealing at 200°C, revealed a 50% reduction in the trap density, but no concurrent change in the recombination lifetime. This constitutes direct evidence of trapping and recombination being caused by physically distinct levels.

Finally, further light is shed on this issue by the behavior of the open-circuit voltage (V_{OC}) of solar cells fabricated on these multicrystalline substrates. This parameter is determined by the minority carrier lifetime when the cell is operating in low-injection, which is usually the case near the trap density for this material. It is possible to measure the V_{OC} as a function of light intensity, which then becomes analogous to the lifetime versus injection-level data[10]. If the anomalous behavior in question were caused by recombination, as suggested by the single-level model, then the V_{OC} versus illumination curve would follow the curve implied by the lifetime versus injection-level measurements. However, we find that this is not the case, and in fact the measured V_{OC} curve and that implied by the lifetime measurements diverge significantly below the trap density[9]. This behavior is consistent with the two-level model, in which the divergence is explained by the massive over-estimation of the lifetime due to the build-up of majority carriers, caused in turn by the shallow trapping centers. In the single-level model, it is possible to generate such a divergence also, by virtue of differences between the majority and minority carrier lifetimes. However, the onus would be on those proposing such a model to show that it could achieve this in an accurate and self-consistent manner.

TABLE I. Trap densities and recombination lifetimes for four multicrystalline silicon wafers of resistivity 0.8Ωcm. From Ref. 2.

Sample	Trap Density N_t (cm^{-3})	Recombination Lifetime (µs)
6A	4.0×10^{15}	0.75
6B	1.7×10^{15}	51
6C	9.0×10^{14}	41
6D	5.1×10^{14}	2.0

It is certainly possible, even likely, that the unusual injection-level dependence due to a single level, as described by Karazhanov, occurs in practice. However, it does not provide a convincing explanation for the ubiquitous effects observed in solar grade cast multicrystalline silicon. In this material, the evidence strongly suggests a two-level model in which a physical distinction exists between those centers responsible for the ‘trapping’ effect, and those which cause recombination.

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