Free carriers and defects exchange interaction in illuminated photojunction

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The study concerns exchange interaction of free minority carriers with extended and local defects states located in illuminated photojunction. The measured open circuit voltage V_{oc} illumination intensity dependences are compared with the suitable theoretical model illustrating the interaction results.
The thermal equilibrium Fermi level energy position F in the forbidden gap of a semiconductor determine the different concentrations of free electrons n_0 and holes p_0 in the conduction and valence bands of photojunction. In the case of the sample illumination, the same numbers of free electrons and holes are generated in the sample proportionally to the number of absorbed photons. Different conditions of exchange interaction of generated electrons and holes in the crystal lead to the creation of crystal steady state conditions and finally different relative increase of densities of free electrons n_1/n_0 and free holes p_1/p_0 in the conduction and valence bands. This steady state condition relative increase of concentrations determines the shift of Fermi level values F to new positions of quasi Fermi levels, different for free electrons and holes. These shifts, generated in the photojunction components, contribute to the open circuit voltage V_{oc}. Changes of illumination intensity allow to determine the dependence of V_{oc} on illumination intensity. The shift of the quasi Fermi level through the forbidden gap leads to the exchange interaction of free carriers with defect states [1-5] located in the gap. The changes of V_{oc} induced by the increase of the illumination intensity will reveal these interactions energy position.

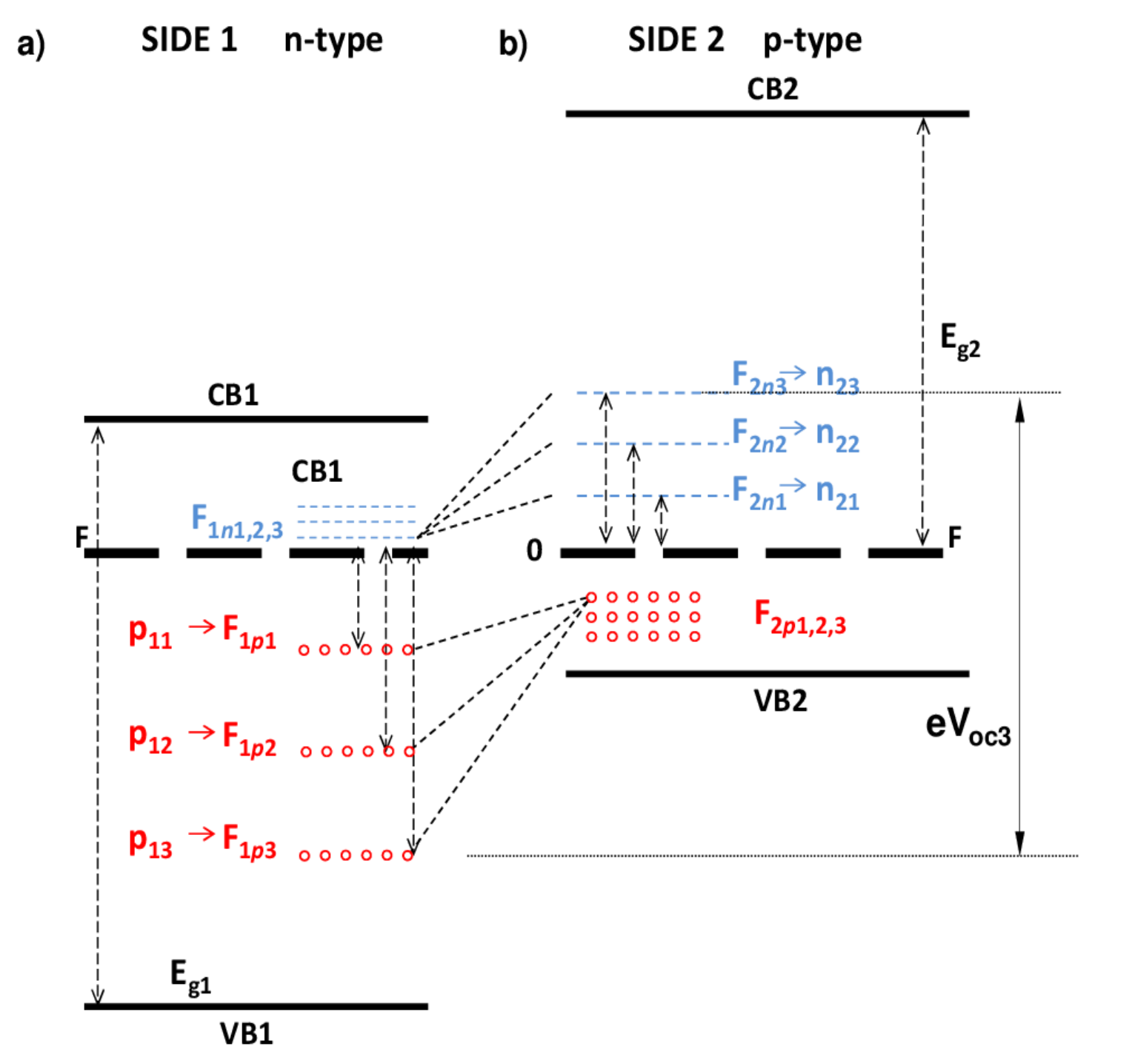

Fig. 1. The illustration of photojunction electronic structure changes under illumination. For SIDE 1 n-type, the sequential changes of generated concentration of minority holes from p_{10} to p_{11}, p_{12} and p_{13} lead to the corresponding changes of hole quasi Fermi level value equal F_{1p1}, F_{1p2} and F_{1p3} and for small changes for majority electrons $F_{1n1,2,3}$.
In analogy, for SIDE 2 p-type, the changes of generated concentration of minority electrons from n_{20} to n_{21}, n_{22}, n_{23} lead to the corresponding changes of electron quasi Fermi levels positions F_{2n1}, F_{2n2}, F_{2n3} and to small changes of $F_{2p1,2,3}$ for majority carriers holes.
The generated quasi Fermi level differences for holes ($F_{1p3} - F_{2p3}$) and analogical for electrons ($F_{2n3} - F_{1n3}$) (red and blue at **Fig.1**) contribution to created open circuit voltage value:
$eV_{oc3} = (F_{2n3} - F_{1n3}) + (F_{1p3} - F_{2p3})$.

$F_{1p1} = kT\ln(p_{11} / p_{10})$; $F_{1n1} = kT\ln(n11 / n10)$; $F_{2p1} = kT\ln(p_{21} / p20)$; $F_{2n1} = kT\ln(n_{21} / n_{20})$

Lets take illustration of used realistic values: e.g. for minority carriers tenfold increase of p_{10} [$\ln(p_{11}/p_{10})$ = ln(10) = 2.303] and kT = 26meV] we obtain F_{1p1} increase by ~60meV. For majority carriers $n_{10} >> p_{10}$ and F_{1n1} can be neglected.

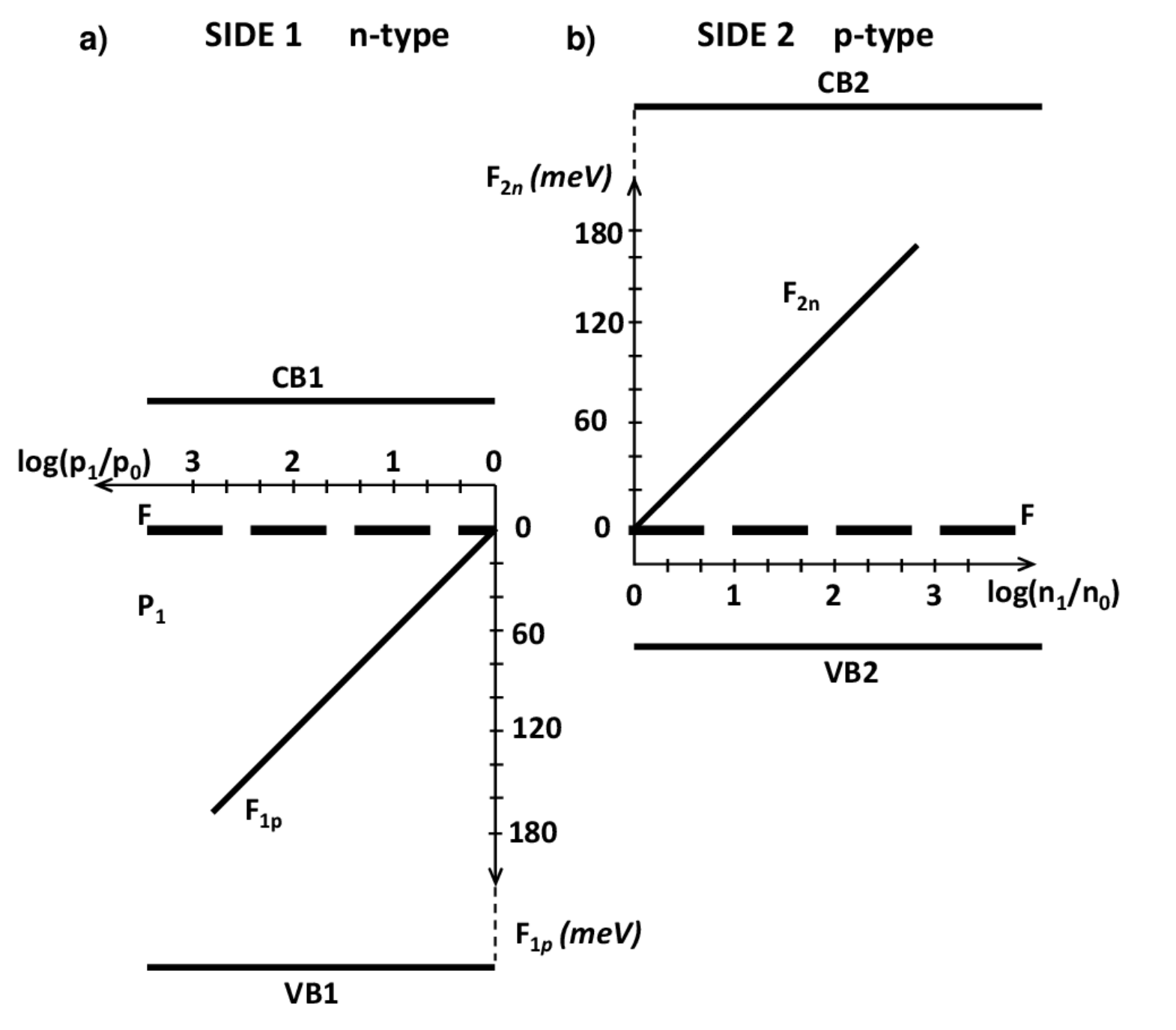

Fig. 2a. The increases of quasi Fermi level of minority carriers F_{1p} and F_{2n} with increase of the minority carriers concentration. For kT = 26meV and $\ln(n_1/n_0)$ = ln10 = 2.303 we have $F_{2n} = (kT)\ln(n_1/n_0)$ = ~ 60 meV

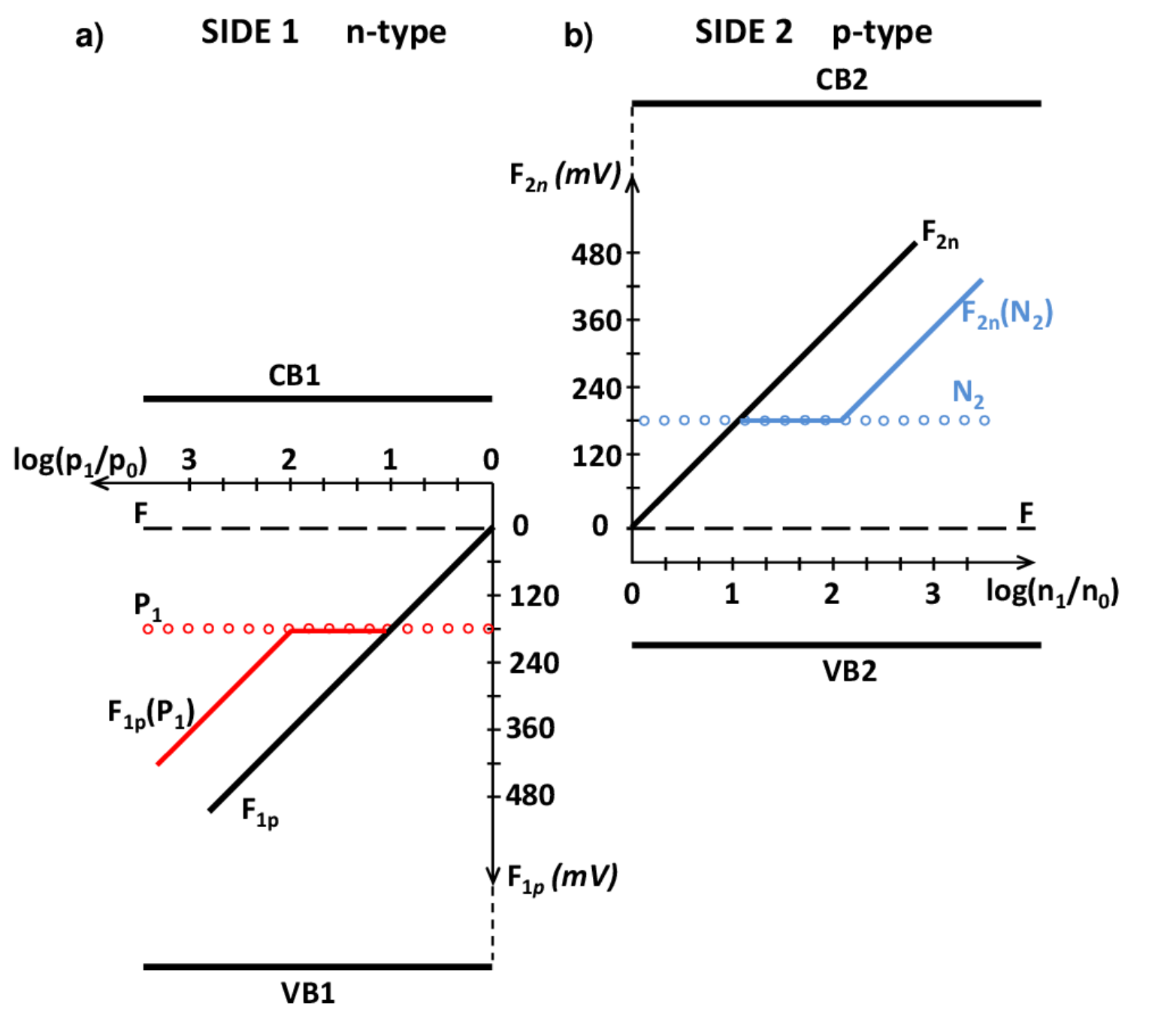

Fig. 2b. The defect recombination centers P_1 or N_2 are damping generated minority carrier concentration. It leads to decrease of corresponding values of F_{1p} and F_{2n} and the open circuit photovoltage value.

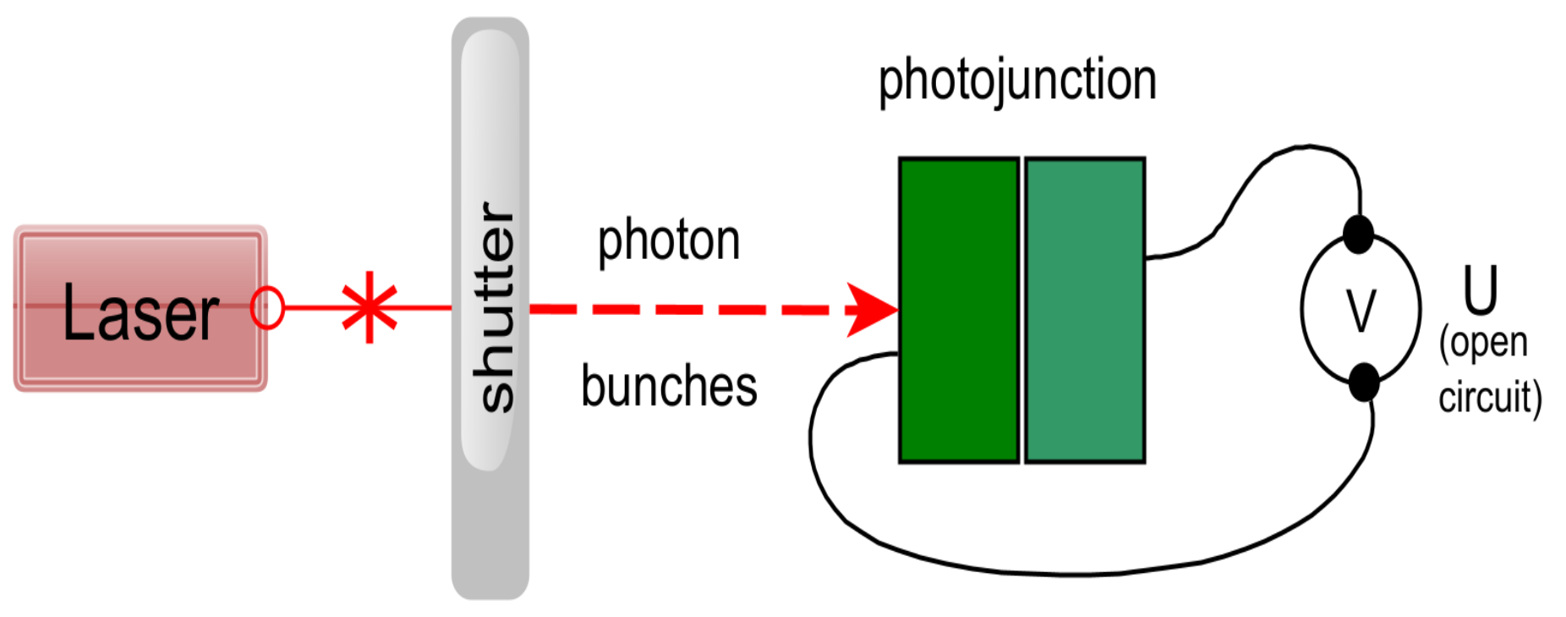

Fig. 3. The experimental set up. The time of open shutter allow to increase free carriers concentration from n_{10} and p_{10} to the corresponding n_{11} and p_{11} and it leads to corresponding step shifts of the quasi Fermi levels of F_{1n1} and F_{1p1} respectively, from F=0eV of the thermal equilibrium Fermi level energy.

Illumination of photojunction ZnTe(p)/CdTe(n) of the top layer side ZnTe (E.g.=2.25eV), transparent for laser emitted photons of energy hv = 1.91eV - do not generate electrons and holes in ZnTe and generate it only in CdTe (E.g. = 1,45eV).
To illustrate expected quasi Fermi level shifts values lets take concentration parameters :
$n_{10}=10^{16}cm^{-3}$, $p_{10}=10^{6}cm^{-3}$, $p_{11}=10^{8}\ cm^{-3}$, $n_{11}=(10^{16}+10^{8})cm^{-3}$
In this case we have:
for minority: $F_{1p1} = kT\ \ln(p_{11} / p_{10}) = 26meV \cdot \ln 100 = 120meV$,
for majority: $F_{1n1} = kT\ \ln(n_{11} / n_{10}) = 26meV \cdot \ln((10^{16}+10^{8})/ 10^{16}) \sim 26meV \cdot \ln(1) \sim 0$.
The energy shift of quasi Fermi level of minority carriers F_{1p1} dominates as a contribution to the generated V_{oc} value and the parameters like F_{1n1} , F_{2n1} and F_{2p1} can be neglected.

Properly selected monochromatic laser radiation (photon energy and radiation intensity) allow to increase steps of quasi Fermi level of minority carriers of one side only of the junction material. It allows for more accurate study of electronic parameters of the material and (relatively) neglect influence of other material parameters of photo junction.

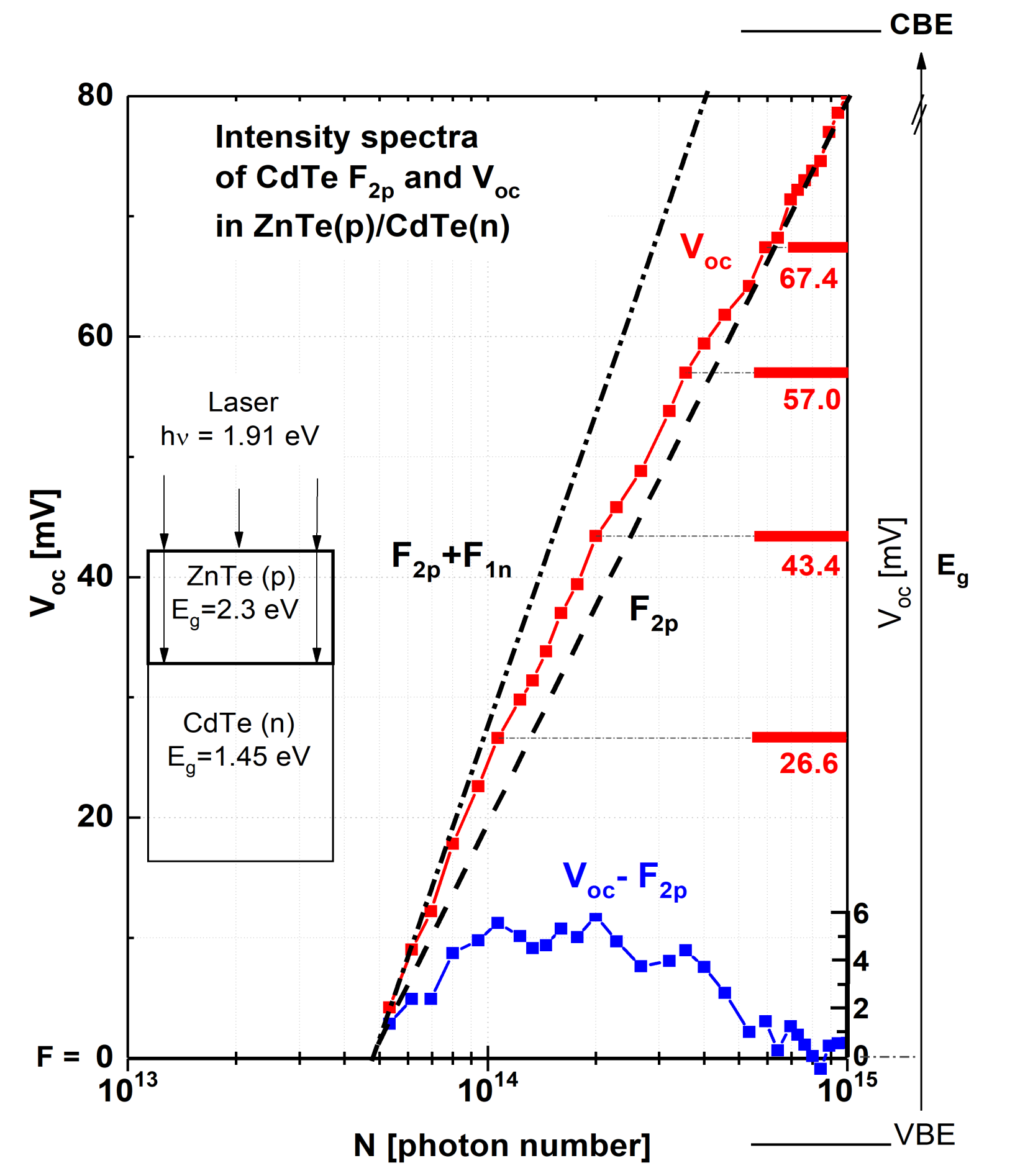

Fig. 4a. Plot of V_{oc} intensity spectra of ZnTe(p)/CdTe(n) junction. Photons of energy hν=1.91eV, transmitted through ZnTe and absorbed by CdTe (see inclusion). The red line corresponds to the experimental curve, black line - predicted by a model. Four V_{oc} steps (26.6; 43.4; 57.0 and 67.4meV) indicate the energy positions of the defects damping generated voltage by lowering concentration of the minority carriers.

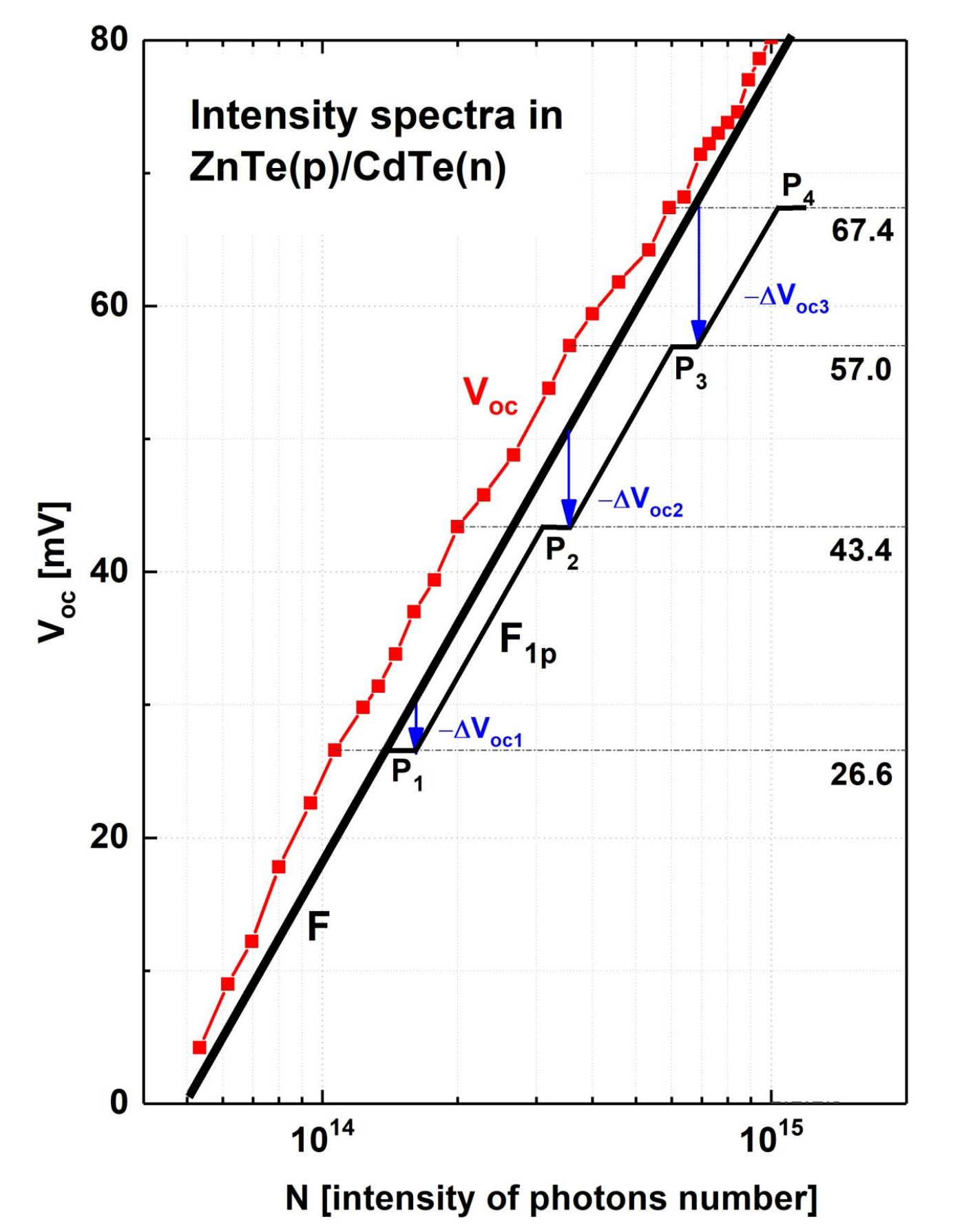

Fig. 4b. Comparison of measured V_{oc} illumination intensity dependence (red) and correlated to it model of F_{1p}(black). The steps occurs as results of exchange interaction of defect states with free carriers in the region of coincidence with quasi Fermi level F1p position.

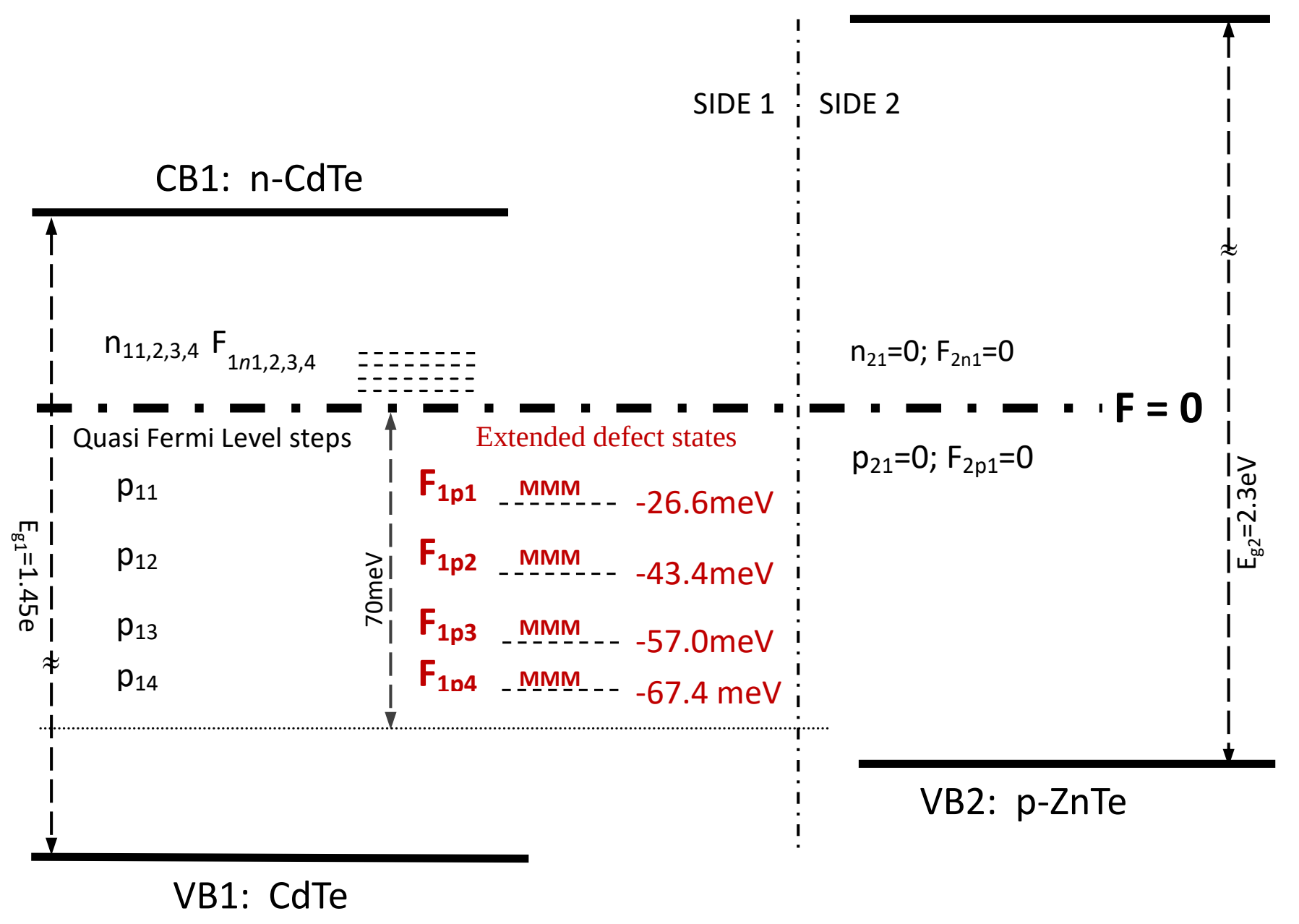

Fig. 5. Electronic structure with the ZnTe and CdTe band gaps and the common equilibrium Fermi level. The measured four defects levels are located in the CdTe band gap below Fermi level in the region from 0 down to 70meV. The states can be correlated to the dislocation related extended defects in ZnTe/CdTe heterojunction [3-5].

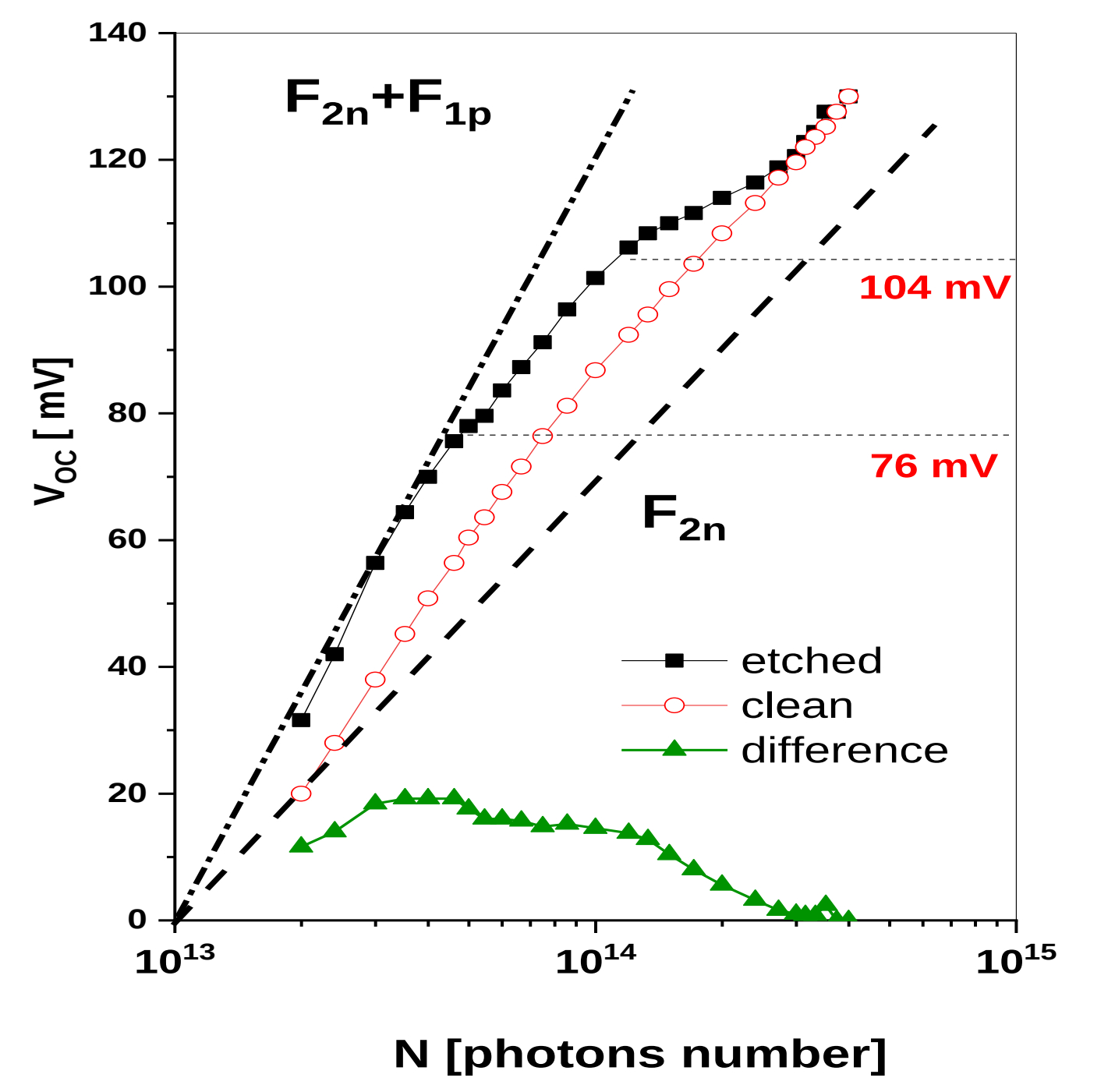

Fig. 6a. Plot of V_{oc} illumination intensity dependence of Si p/n homojunction. The red line corresponds to as grown homojunction V_{oc} illumination intensity dependence. Black line corresponds to the photojunction after etching. Lowest curve is the difference between black and red curves. Steps on the black line (76meV and 104meV respectively) show approximate energy positions of defect states located below F=0.

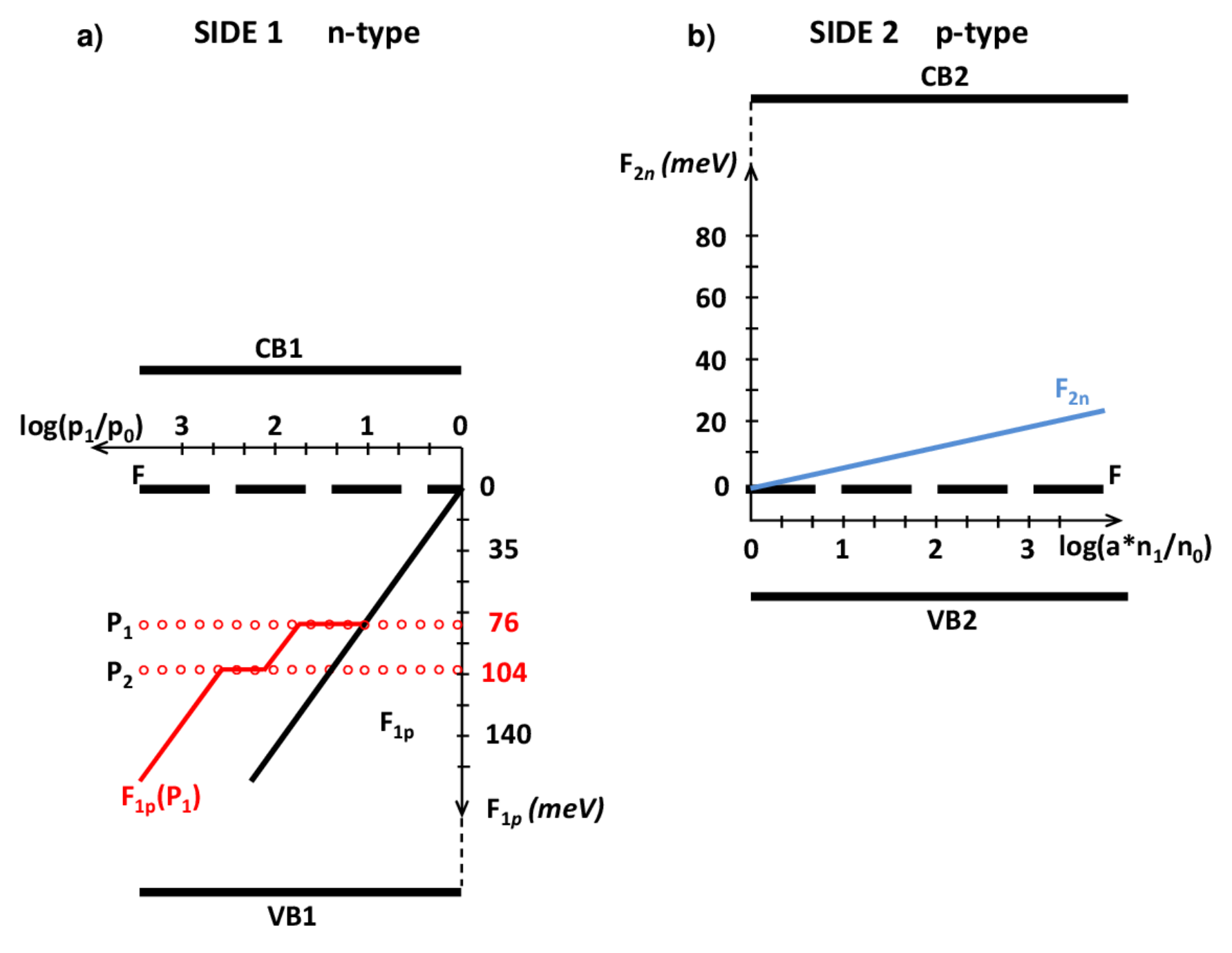

Fig. 6b. Electronic structure of the band gap of Si(n) and Si(p) with the common equilibrium Fermi level. The measured two steps are located in Si(n) type band gap below Fermi level. The states can be correlated to the local defects in the homojunction.
a is a photon absorption coefficient of the n-type (SIDE 1) layer, identical for each photon bunch.

Summary and Literature

- The increase of the number of illuminating photons leads to shift of the quasi Fermi level through the forbidden band gap region. The change of the quasi Fermi level energy contributes to the value of the generated open circuit voltage of photo junction.
- The change of quasi Fermi level energy F_{2n} of minority electrons and F_{1p} of minority holes gave the main contribution to the generated voltage of photo junction.
- The photo junction can be treated as a double cell with contribution of voltages generated by electrons in the conduction bands and holes in the valence bands.
- The electronic defects (e.g. extended or local defects) present in the region of photo junction will lead to the exchange interaction with free electrons lowering their density and creating step change of the quasi Fermi level.
- The experiment allows to estimate energy position of electronic levels of structures like extended defects, dislocations, quantum wells etc.

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