Free carriers and defects interaction in illuminated photojunction

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The thermal equilibrium Fermi level energy position F in the forbidden gap of semiconductor determine the different concentration 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 number 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 leads to the creation of crystal steady state conditions and final different relative increase of densities of free electrons n_1/n_0 and free holes p_1/p_o in conduction and valence bands. These steady state condition relative increase of concentrations determine 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 value V_{oc}. Changes of illumination intensity allow to determine V_{oc} illumination intensyty dependence. The scan of forbiden gap by quasi Fermi level leads to the exchange interaction of free carriers with defect states [1-3] located in the gap. Illumination intensity dependent changes of V_{oc} will illustrate the peaks or structure of these interactions.

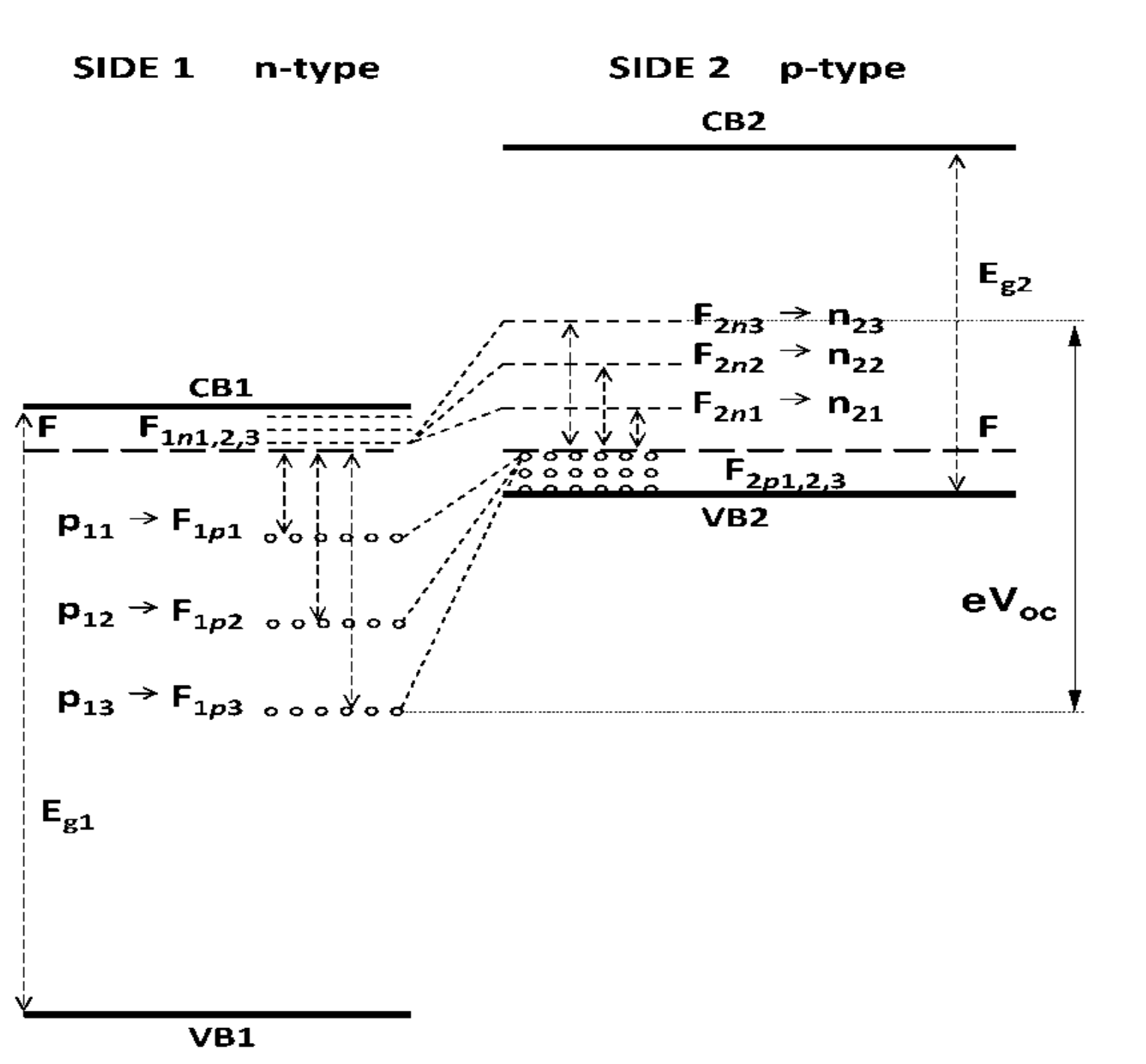


Fig. 1. The illustration of photojunction electronic structure changes under illumination. For SIDE 1 n-type, the sequential changes of generated concentration values of minority holes from p_{10} to p_{11}, p_{12} and p_{13} leads to the corresponding changes of holes quasi Fermi level value equal F_{1p1}, 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 values of minority electrons from n_{20} to n_{21}, n_{22}, n_{23} leads to the corresponding changes of electrons quasi Fermi levels positions F_{2n1}, F_{2n2}, F_{2n3} and to small changes of $F_{2p1,2,3}$ for majority carriers holes.
$eV_{oc3} = (F_{2n3} - F_{1n3}) + (F_{1p3} - F_{2p3})$

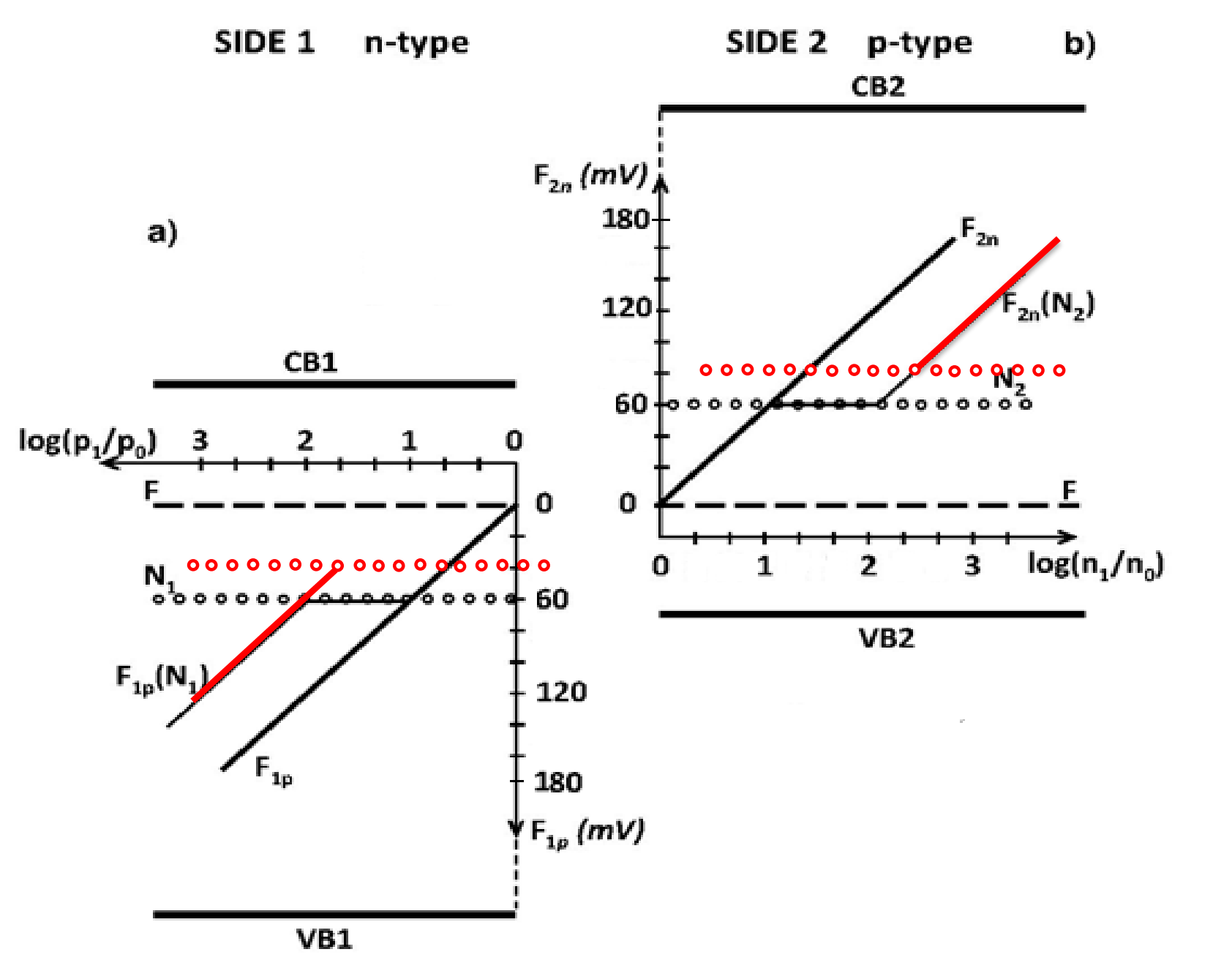


Fig. 2a. and 2b. The increases of quasi Fermi level of minority carriers SIDE 1, n-type, p – holes
$F_{1p}= (kT) \ln(p_1/p_0)$
$F_{2n}= (kT) \ln(n_1/n_0)$ with increase of the minority carriers concentration.

For kT = 26meV and $\ln(n_1/n_0)=\ln 10=2.303$ we have

$$\mathbf{F_{2n}=(kT)\ln(n_1/n_0) =\sim 60\ meV}$$

The introduced defect centers N_1 and N_2 in exchange interaction with free carriers are damping generated minority carriers concentration values and predicted by model values of F_{1p} and F_{2n}, and it shifts to the value of $F_{1p}(N_1)$ and $F_{2n}(N_2)$ line position. Thise pining like effect occures in the region of 60meV and determine energy position of difect state.

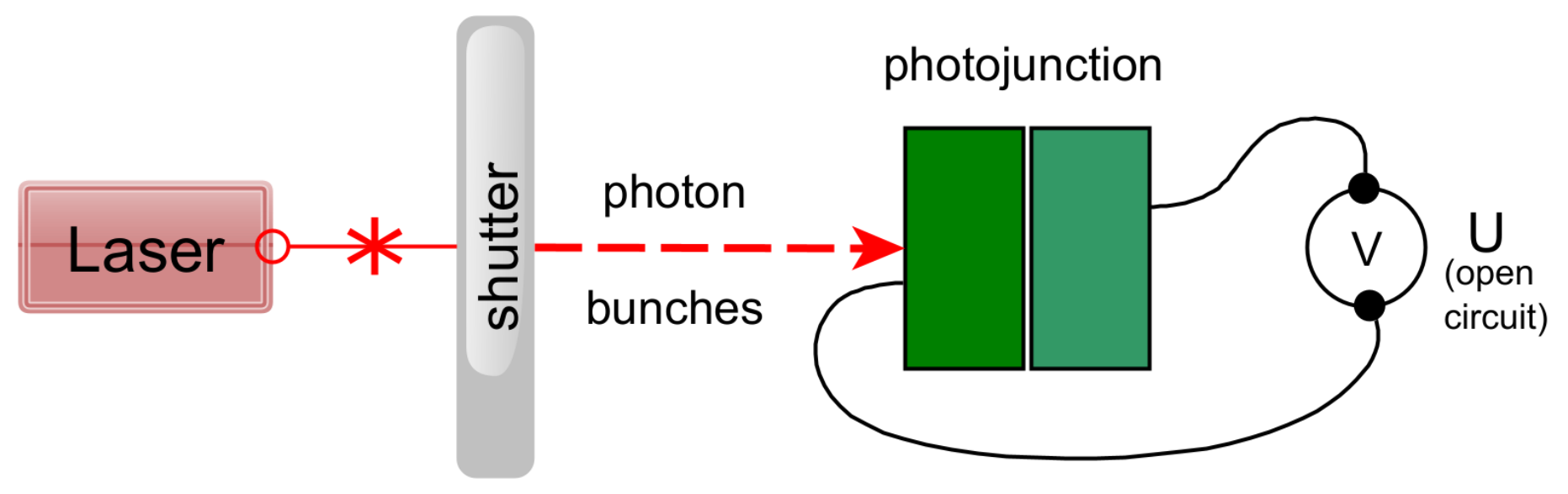
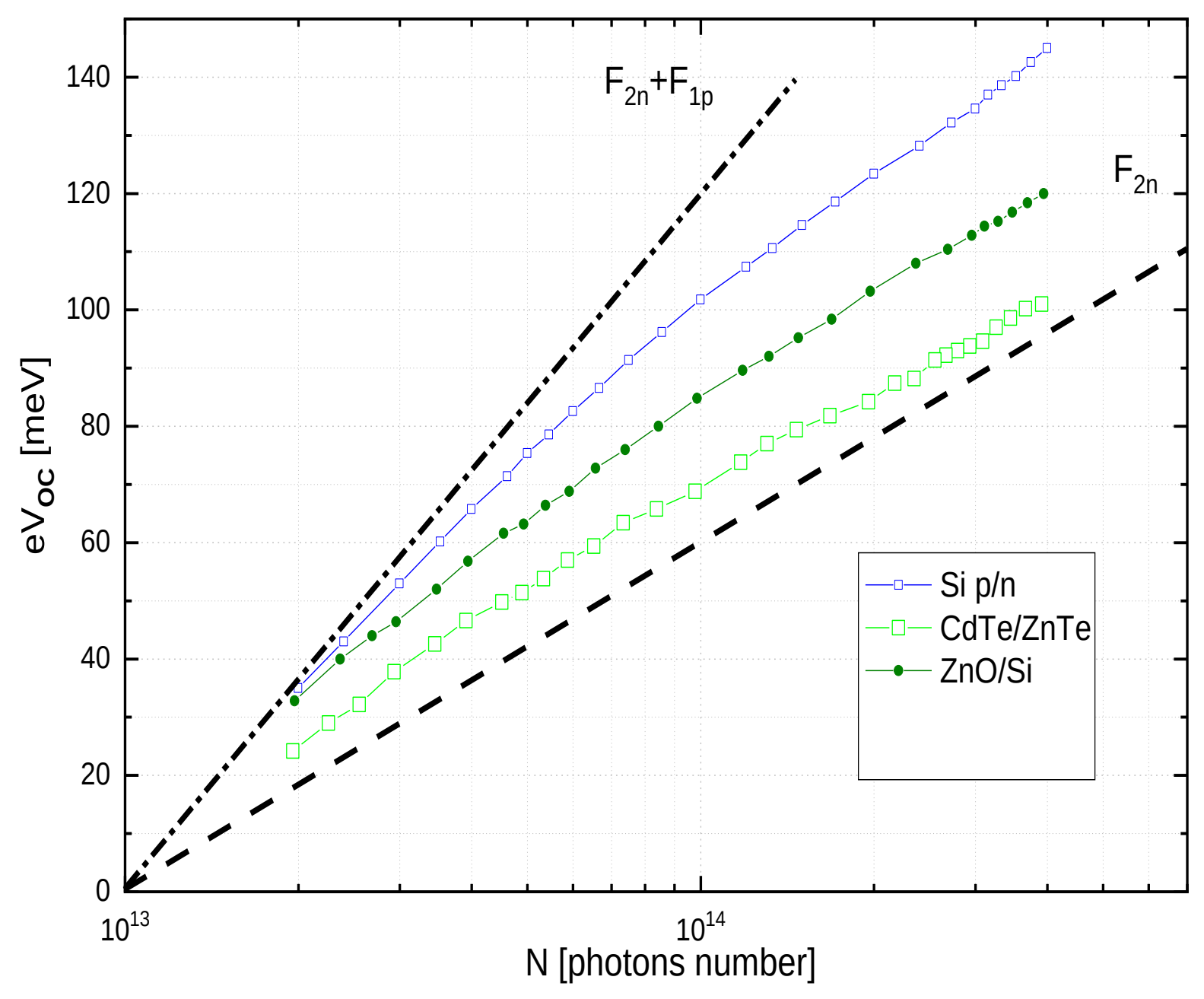


Fig. 3. Experimental Illumniation and electronic set up. The time t_i of open shutter allow to increase the free carriers concentration from n_0 and p_0 to the corresponding n_i and p_i and it leads to corresponding shifts of quasi Fermi levels energy relatively on F_{ni} and F_{pi} from the F=0eV of thermal equilibrium Fermi level energy.



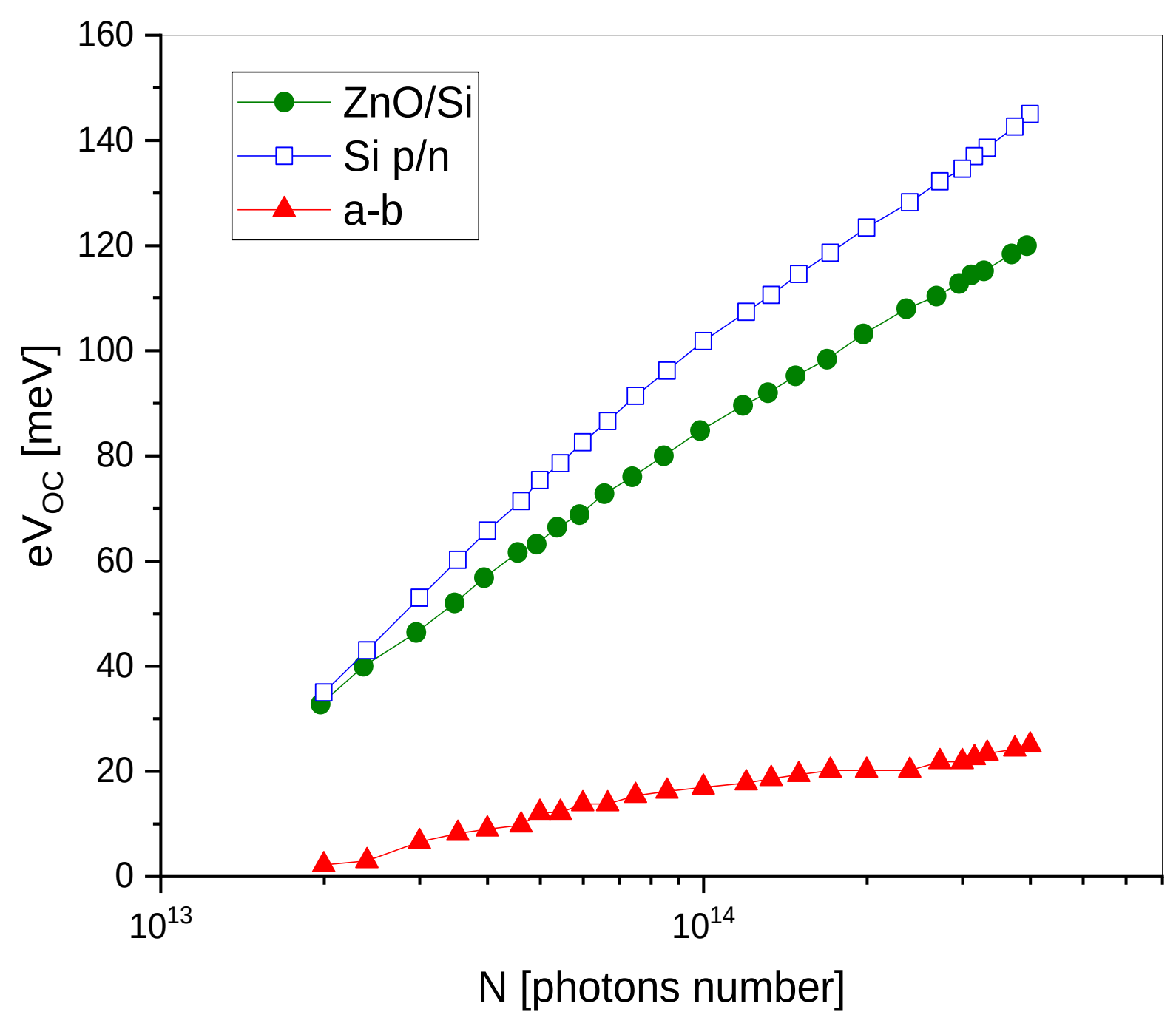
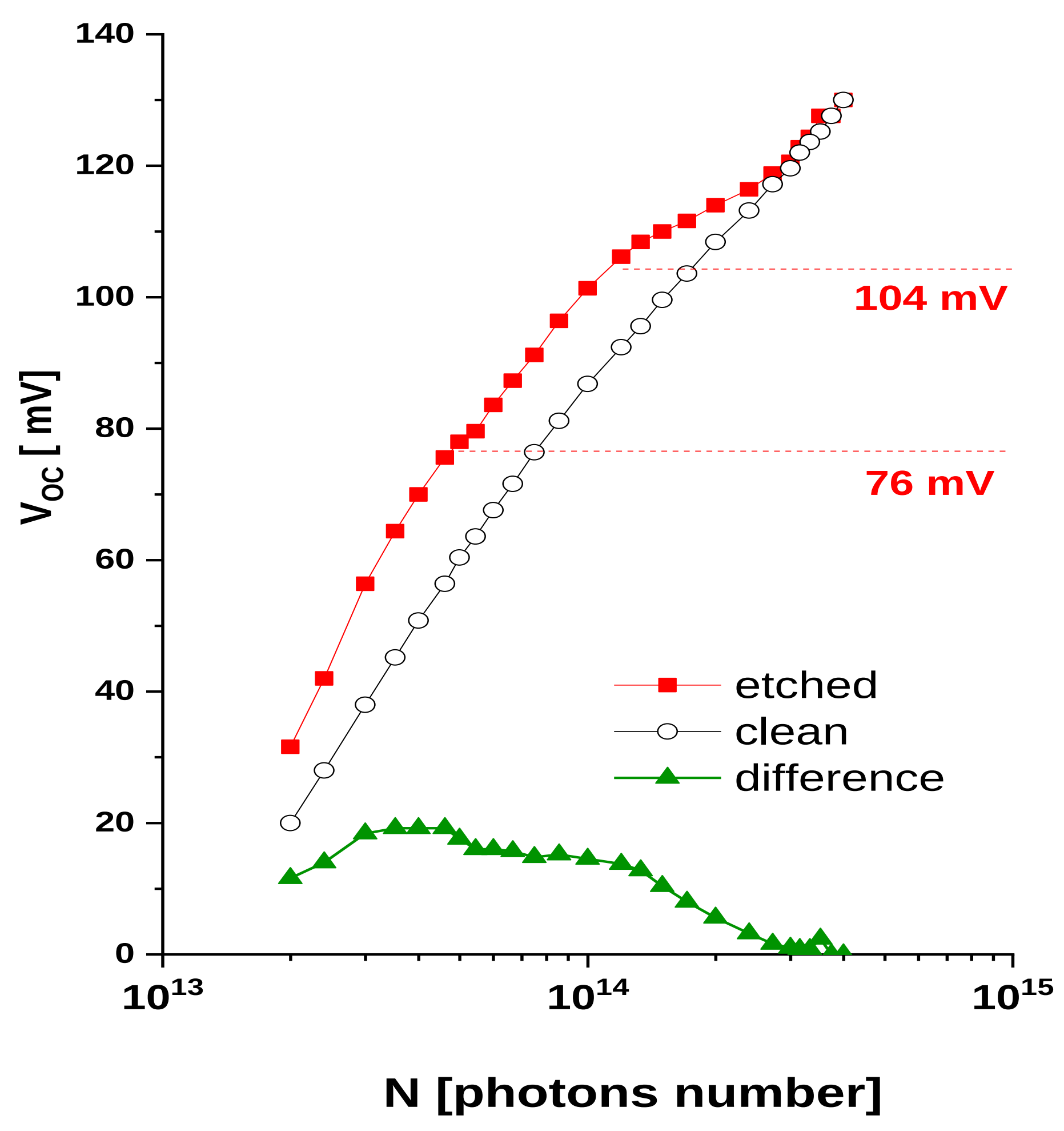


Fig. 4a. - Plot of V_{oc} intensity spectra of Si illumination in ZnO/Si heterojunction, and Si(n) and Si(p) illumination in Si(n/p) homojunction and CdTe illumination in ZnTe(p)/CdTe(n) heterojunction. For the case of heterojunction Si and CdTe curves are paralell to the lower dotted line corresponding to the absorption of only one side of junction Si and CdTe.

Fig. 4b. For the case of homojunction Si p/n the inclination of the line is bigger us it corresponds to the both n sides and p sides absorption (top n side is partialy transparent to p side) and both sides change corresponding quasi Fermi levels contributions, part of F_{1p} + part of F_{2n}. The lowest curve presents the difference of Si p/n - ZnO/Si curves. The changes of majority carriers are negletted.



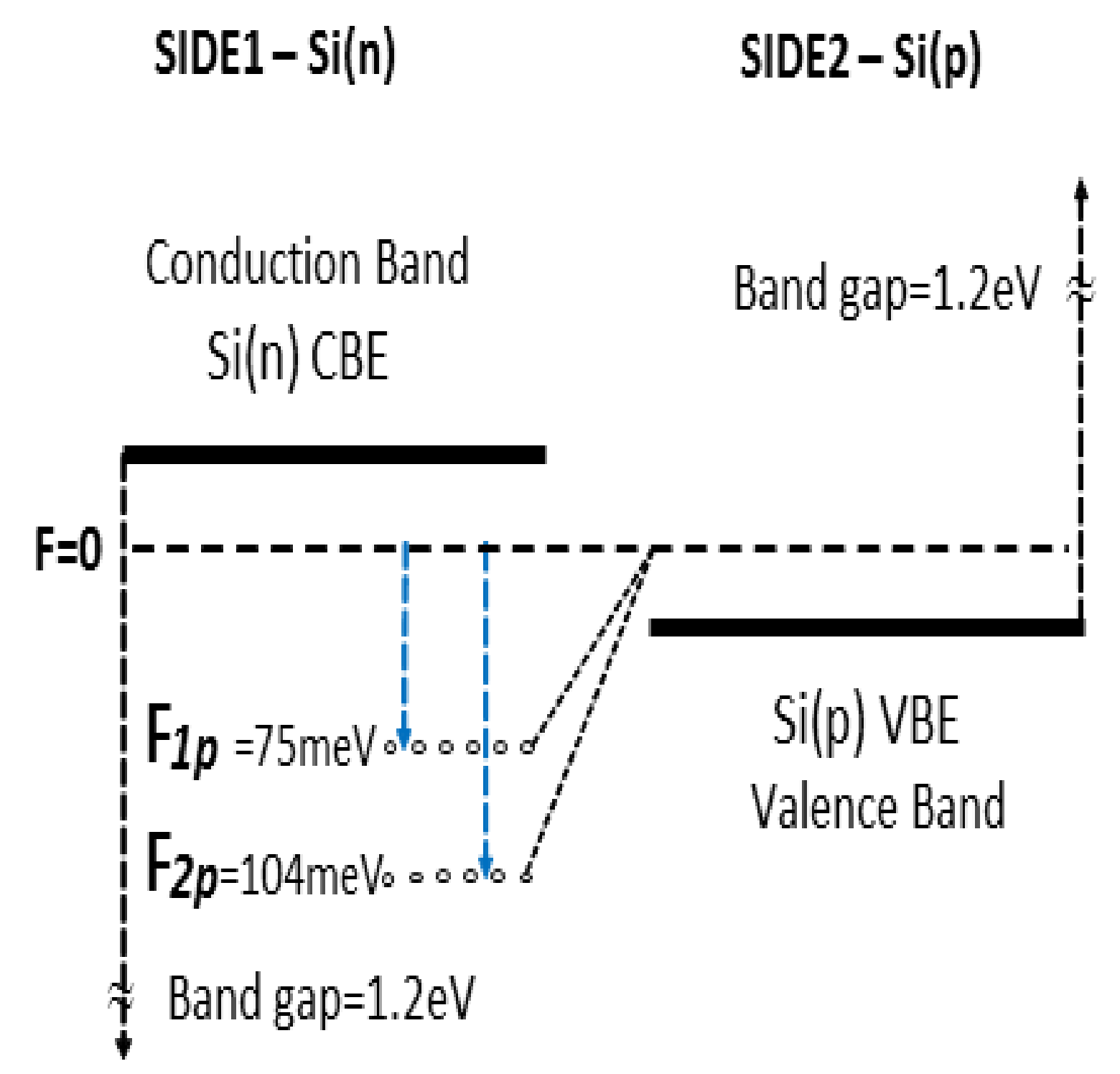
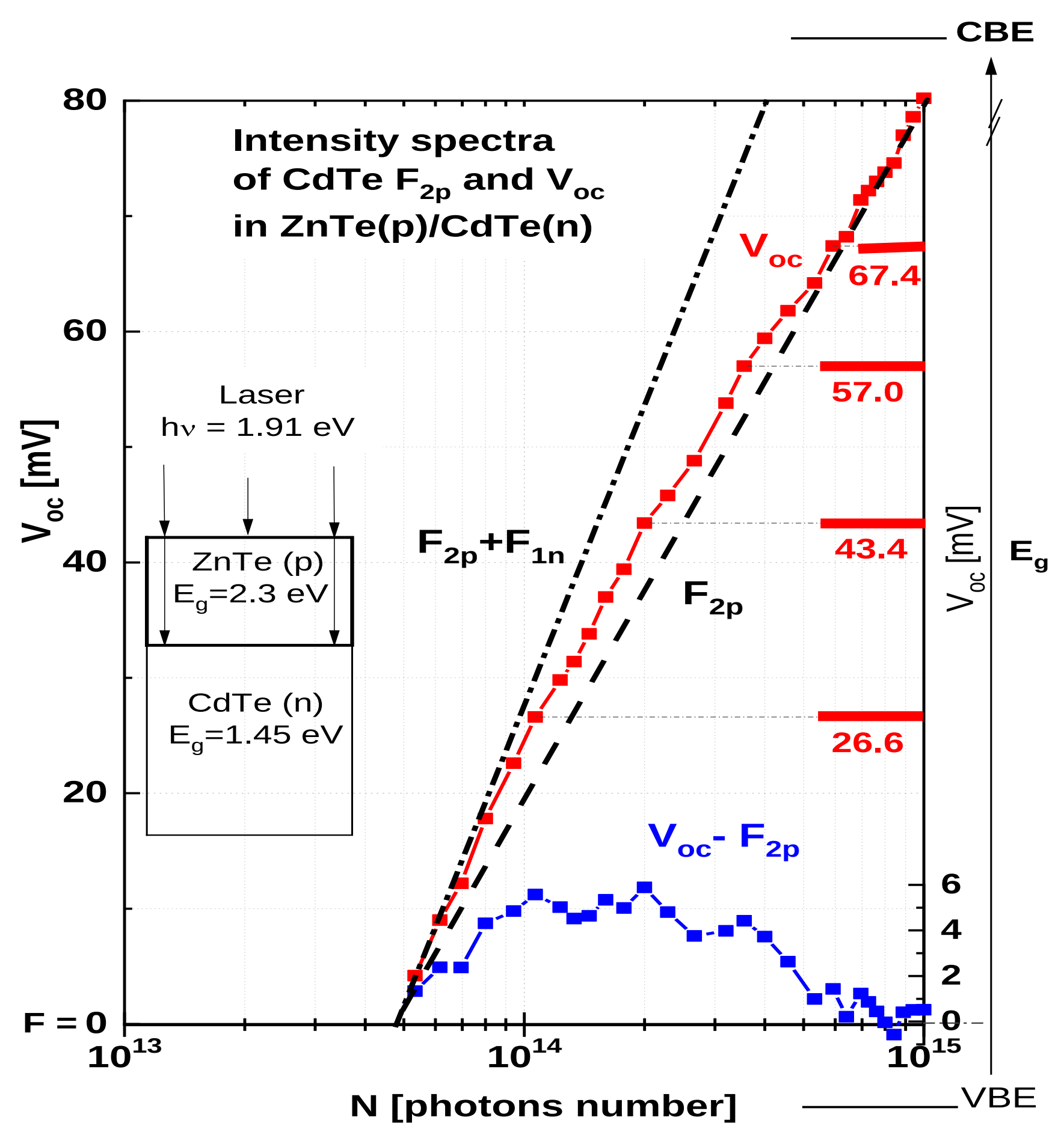


Fig. 5a. Plot of V_{oc} illumination intensity dependence of Si p/n homojunction. The black line corresponds to clean homojunction V_{oc} illumination intensity dependence. Red line corresponds to the photojunction after etching. Lowest curve is the difference between red and black curves. The steps on red line (76 meV and 104 meV) approximate the energy position of defect states located below F=0

Fig. 5b. Electronic structure of band gap of Si n and Si p and common equilibrium Fermi level. The measured two steps (see Fig. 7.) are located in Si n type band gap below Fermi level. The states can be correlated to the local defects in the homojunction**.**



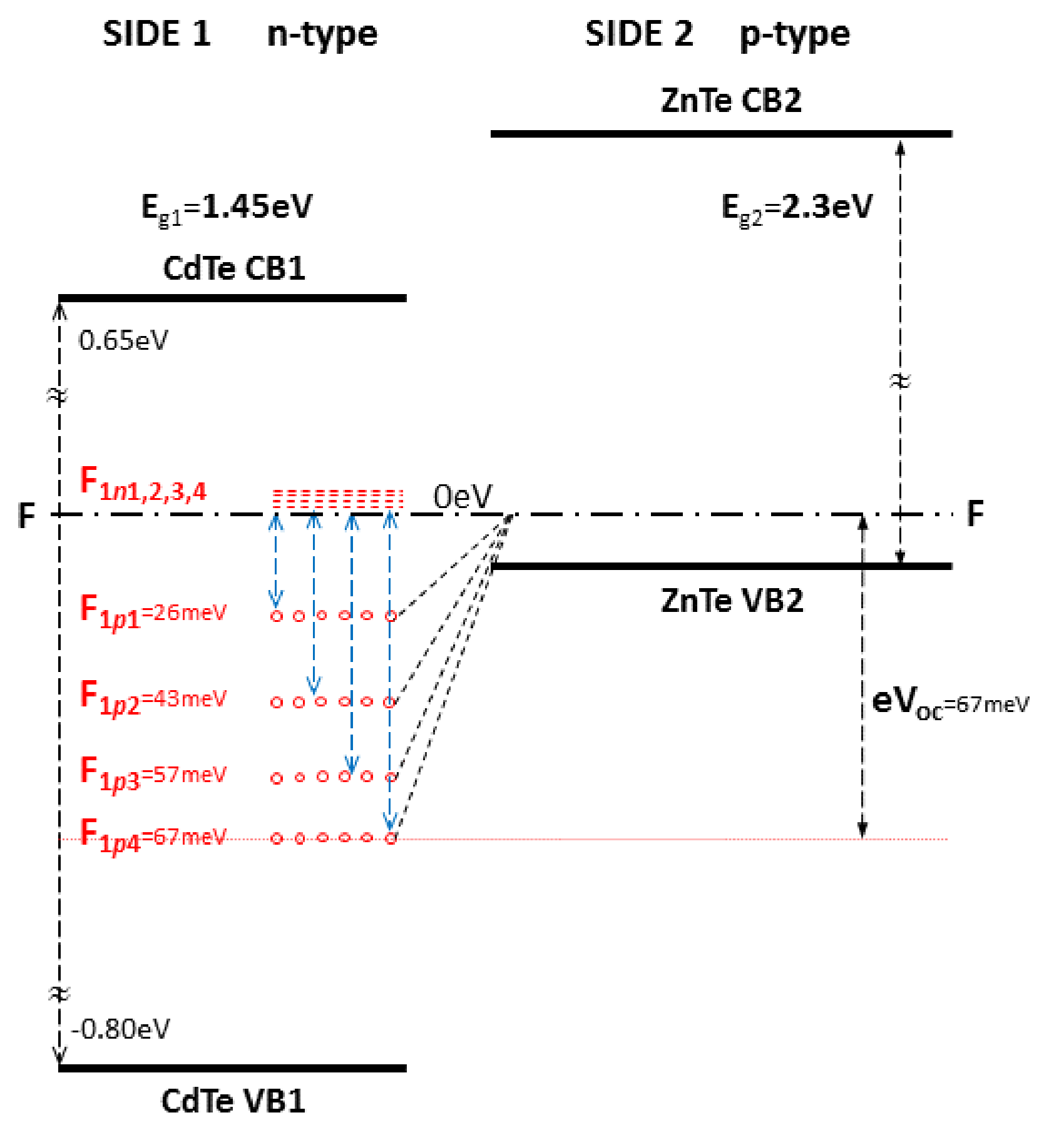


Fig. 6a. Plot of V_{oc} intensity spectra of ZnTe(p)/CdTe(n) junction. Photons of energy hv = 1.91eV, transparent for ZnTe and absorbed by CdTe (see inclusion). The red line corresponds to experimental curve, black line - predicted by model. Four V_{oc} steps (26,6; 43,4; 57,0 and 67,4meV) indicate the energy position of the defects damping generated voltage by lowering concentration of the minority carriers.

Fig. 6b. Electronic structure with the ZnTe and CdTe band gaps and common equilibrium Fermi level. The measured four defects levels (see **Fig. 5a.**) are located in CdTe band gap below Fermi level in the region from 0 down to 70meV. The states can be correlated to the dislocations extended defects in ZnTe/CdTe heterojunction [3-5].

SUMMARY

- The increase of number of illuminating photons leads to the scan of forbidden band gap region by the quasi Fermi level and the change of their energy contributes to the value of the generated open circuit voltage of photojunction.
- The change of quasi Fermi level energy F_{2n} of electrons minority carriers and F_{1p} of minority holes value gave the main contribution to the generated voltage of photojunction.
- The photojunction can be treated as a double cell with contribution of voltages generated by electrons in conduction band and holes in valence band.
- The electronic defects (e.g. extended or local defects), present at the region of pining steps will lead to the exchange interaction with free electrons lowering their density and creating steps of quasi Fermi level change.
- The experiment allows to estimate the energy position of pining steps relatively to the thermal equilibrium Fermi level energy position.

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