Table 13.5 Highest-efficiency devices for different alloy absorber layers

Material	E_g [eV]	Efficiency [%]	V_{OC} [%]	J_{SC} [mA/cm^2]	FF [%]	Reference
$CuInSe_2$	1.02	15.4	515	41.2	72.6	[80]
$Cu(InGa)Se_2$	1.12	18.8	678	35.2	78.6	[1]
$CuGaSe_2$	1.68	8.3	861	14.2	67.9	[196]
$CuInS_2$	1.53	11.4	729	21.8	71.7	[197]
$Cu(InAl)Se_2$	1.16	16.9	621	36.0	75.5	[198]

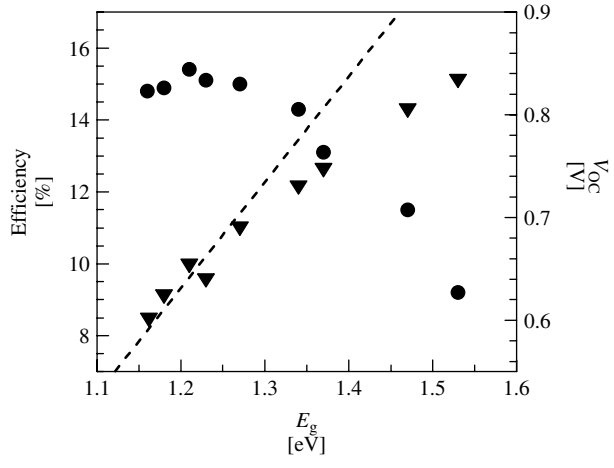

Figure 13.20 Efficiency (▼) and V_{OC} (●) as a function of $Cu(InGa)Se_2$ band gap, varied by increasing the relative Ga content, (From Shafarman W, Klenk R, McCandless B, *Proc. 25th IEEE Photovoltaic Specialist Conf.*, 763–768 (1996) [199]. The dashed line has slope $\Delta V_{OC}/\Delta E_g = 1$

the Ga was confined to the back of the absorber and did not increase the band gap in the space charge region [105]. The effect of increasing band gap in $Cu(InGa)Se_2$/CdS solar cells on V_{OC} and efficiency is shown in Figure 13.20. Efficiency is roughly independent of band gap for $E_g < 1.3$ eV or $Ga/(In + Ga) < 0.5$ [165, 199]. With even wider band gap, V_{OC} increases to greater than 0.8 V, but the efficiency decreases. This indicates poorer electronic properties of the $Cu(InGa)Se_2$ absorber layer, which has two effects: voltage-dependent current collection [165], which causes the fill factor to decrease, and increased recombination [200], which reduces V_{OC} below that expected from equation (13.9) [27]. The dashed line in Figure 13.20 shows a line with slope $\Delta V_{OC}/\Delta E_g = 1$. Ideally, the increase in V_{OC} would have only a slightly smaller slope due to the dependence on J_L in the second term of equation (13.9). Admittance spectroscopy showed a correlation between the recombination and the density of a defect with an activation energy ~0.3 eV, which increases with E_g [200]. Transient photocapacitance measurements showed a defect band centered at 0.8 eV from the valence band, which moves closer to midgap for increasing band gap and therefore becomes more efficient as a recombination trap [201]. As the band gap becomes wider, type inversion of the absorber layer near the interface may no longer occur and interface recombination can become more significant. Analysis of both $CuGaSe_2$ [202] and $CuInS_2$ [203] solar cells showed that the low open-circuit voltages