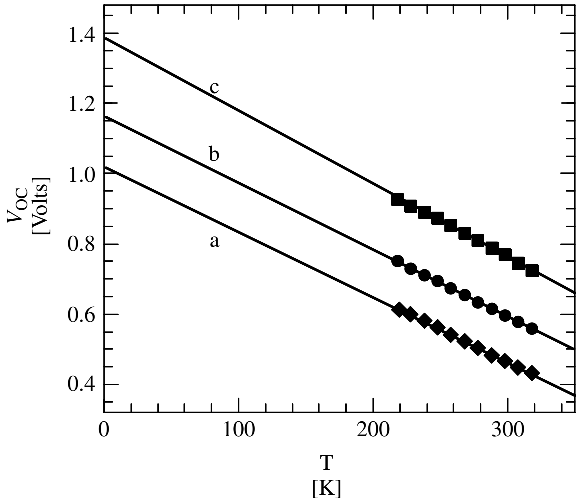

Figure 13.18 Temperature dependence of V_{OC} for the devices shown in Figure 13.16

and (13.8) and assuming $G \ll J_L/V_{OC}$, the open-circuit voltage becomes

$$V_{OC} = \frac{E_g}{q} - \frac{AkT}{q} \ln\left(\frac{J_{OO}}{J_L}\right) \tag{13.9}$$

with the barrier height $\Phi_b = E_g$.

The different recombination paths are effectively connected in parallel so that V_{OC} will be controlled by the single dominant mechanism with the highest current. The values of Φ_b and A can be used to distinguish between recombination in the bulk absorber, in the space charge region of the Cu(InGa)Se_2, or at the Cu(InGa)Se_2/CdS interface [27, 169]. Each of the curves in Figure 13.16 can be fit to equation (13.7) with $A = 1.5 \pm 0.3$. For a wide range of thin-film solar cells, it has been demonstrated that $V_{OC}(T \to 0) = QE_g$ and $1 < A < 2$ similar to the data above. Specifically, this has been shown for $CuInSe_2$ [116, 170] and Cu(InGa)$(SeS)_2$ [171] devices, independent of the (CdZn)S buffer-layer band gap [170], and for a variety of different absorber-layer deposition processes [172]. These results for Φ_b and A indicate that Cu(InGa)Se_2/CdS solar cells operate with the diode current controlled by Shockley–Read–Hall type recombination in the Cu(InGa)Se_2 layer [168]. This recombination is greatest through deep trap states in the space charge region of the Cu(InGa)Se_2 where there are comparable supplies of electrons and holes available, that is, $p \approx n$. The variation in A between 1 and 2 depends on the energies of the deep defects that act as dominant trap states [173]. As these states move toward the band edges, $A \to 1$ and the recombination becomes closer to band-to-band bulk recombination.

These observations exclude recombination in the neutral bulk region of the absorber layer, which should give $A = 1$. Interface recombination would give $\Phi_b < E_g$[Cu(InGa)Se_2] with a dependence on the (CdZn)S band gap, although A might vary from 1 to >2 [174]. Back surface recombination at the Mo/Cu(InGa)Se_2 interface will