region, (2) negligible light induced degradation, (3) reduced materials cost, since μc-Si can be made using SiH_4, which is a relatively low-cost gas compared to GeH_4, and (4) μc-Si cells can be made with high *FF*. On the other hand, the concerns associated with using μc-Si compared to a-SiGe bottom cell are (1) μc-Si cells require much thicker *i*-layers (several micrometers thick) to absorb the sunlight; this is an effect of the lower interband absorption coefficients in (indirect band gap) crystals compared to amorphous semiconductors, (2) the deposition rate for μc-Si material is generally low, so that a much longer time is needed to complete the deposition of a thick μc-Si layer than what is needed for an a-SiGe layer, and (3) μc-Si solar cells have lower V_{OC} (around 0.53 V) than do a-SiGe cells yielding the same J_{SC}.

Beside VHF technique, μc-Si has also been deposited using other high deposition rate methods such as HW CVD [178], GasJet/MW deposition [179], and high-power/high-pressure RF deposition [180]. A typical deposition rate for an a-SiGe *i*-layer is 3 Å/s; to complete a μc-Si cell with comparable deposition time, one would need to deposit μc-Si with at least ~20 to 30 Å/s deposition rate so that it would not be rate-limiting during production.

12.5.5 Micromorph and Other μc-Si-based Multijunction Cells

Meier *et al.* [181] used an a-Si *pin* junction as the top component cell and a μc-Si *pin* as the bottom component cell for a-Si/μc-Si tandem cells; they named these cells *Micromorph* devices. The 1.7 eV/1.1 eV band gaps for the top/bottom cell provide a nearly ideal band gap pair for tandem cells (see contour diagram in Figure 12.22 above).

In order for an a-Si/μc-Si tandem cell to have comparable performance as an a-Si/a-SiGe cell, the bottom cell μc-Si must have at least 26 mA/cm^2 current density. Since μc-Si has an indirect band gap, generating such a high current requires the μc-Si layer to be several micrometers thick. In addition, advanced light enhancement schemes need to be used. In order to maintain current matching in a micromorph cell, the top a-Si component cell must generate 13 mA/cm^2 (i.e. half the current for a stand-alone μc-Si). In addition, this a-Si cell needs to be stable under light so that the tandem cell could be stable.

Two approaches were taken to accomplish this [182, 183]. First, the a-Si *i*-layer is made at a relatively higher temperature, so that there is a lower H concentration (and a reduced band gap, ~1.65 eV). Secondly, a semireflective layer was inserted at the tunnel junction between the top and the bottom cell. This semireflective layer permitted current matching (enhancing the top component cell current at the expense of the bottom cell). With these two approaches, 13 mA/cm^2 J_{SC} was obtained from the top cell with a 3000 Å thick a-Si layer. Innovative approaches need to be taken to further increase the current beyond the present level. With the micromorph tandem design, solar cells with 11 to 12% stable efficiency have been fabricated [163, 183].

One can also combine a-Si and μc-Si cells to fabricate a-Si/μc-Si/μc-Si triple cells. Such a design would relax the stringent requirement on the a-Si top cell due to current matching since it now only needs to generate one-third of the bottom cell current. However, the presently low V_{OC} of a μc-Si cell militates against the triple-junction design.