or a (1 × 2) surface symmetry. For the (2 × 1) reconstruction, the dimer bonds are parallel and rows of dimers run perpendicular to the step edges. Adjacent terraces on an (100) As-terminated Ge surface can be composed of orthogonal reconstructions; adjacent terraces on a (100) GaAs are always of the same type. An As-terminated Ge surface prepared in a UHV or MBE environment usually exhibits a single-domain, (1 × 2) symmetry. An MOCVD-prepared surface will initially be (1 × 2), but tends toward (2 × 1) symmetry with a transition time that ranges from one minute to tens of minutes and that depends on temperature, AsH_3 partial pressure, and substrate temperature. Intermediate states, of course, are composed of a mixture of (1 × 2) and (2 × 1) domains, a condition that is conducive to the formation of APDs in a GaAs heterolayer. Also, as mentioned above, AsH_3 etches Ge. This etching causes significant step bunching or faceting and microscopically rough surfaces.

9.6.6 Tunnel-junction Interconnects

The purpose of the tunnel-junction interconnect between the GaInP and GaAs subcells is to provide a low-resistance connection between the *p*-type BSF of the GaInP cell and the *n*-type window layer of the GaAs bottom cell. Without the TJIC, this *p-n* junction has a polarity or forward turn-on voltage that is in opposition to that of the top or bottom cells and, when illuminated, would produce a photovoltage that could roughly negate the photovoltage generated by the top cell. A tunnel junction is simply a p^{++} n^{++} junction where p^{++} and n^{++} represent heavily or degenerately doped material. The space charge region for a p^{++}-n^{++} junction should be very narrow, ~10 nm. In forward bias, the normal thermal current characteristic of a *p-n* junction is "shorted" by tunneling through the narrow space charge region. Hence, the forward IV characteristic of a tunnel junction behaves much like a resistor for current densities less than some critical value, called the peak tunneling current, J_p. The functional form of J_p is dominated by an exponential term of the form:

$$J_p \propto \exp\left(-\frac{E_g^{3/2}}{\sqrt{N^*}}\right) \tag{9.24}$$

where E_g is the band gap and $N^* = N_A N_D/(N_A + N_D)$ is the effective doping concentration [110]. The value of J_p must be larger than the photocurrent of the tandem cell. For a concentrator cell operating at 1000 suns, $J_{SC} \sim 14$ A/cm^2. If $J_p < J_{SC}$, the behavior of the tunnel junction current switches to that dominated by the usual thermionic emission and the voltage drop across the tunnel junction increases to that of a typical *p-n* junction.

The best tunnel junctions for very high efficiency solar cells are relatively defect-free. Lifetime limiting, midgap defects usually only add to the excess current. There is no evidence in the literature that point or extended defects add to J_p or increase the conductivity in the tunneling portion of the I-V curve. High excess currents can mask a low J_p, but usually the junction conductivity is also unacceptably low. On the other hand, it is possible that high concentrations of point or extended defects can compensate donors or acceptors in the junction leading to increased depletion width and lower tunneling currents. In addition, defects can reduce the thermal stability of the tunnel junction and the quality of the overlying layers. Therefore, in general, it is usually best to grow the TJICs free of point or extended defects.