which implies very little recombination. The contrast increases with increased impurity segregation.

A good deal of preliminary understanding of the design of a TF-Si solar cell can be acquired through modeling a single-crystalline TF-Si cell. Such a cell may be considered to have uniform material properties, but inclusion of metallization can introduce large spatial nonuniformities (because shadowing effects can be more pronounced in a thinner cell). However, for a first approximation, 1-D analysis can yield reasonably accurate results. In the beginning of the chapter, we used *PV Optics* and PC1D to show dependence of J_{SC} on the cell thickness and V_{OC} on the thickness and the surface-recombination velocity, respectively [64, 65]. Another electronic modeling package, used by most a-Si cell designers, is AMPS (analysis of microelectronic and photonic structures) [66]. To date, PC1D is only a 1-D package and is valid for uniform, homogeneous material without GBs or intragrain defects. Because PC1D does not include detailed light-trapping, a good 1-D modeling would still require a combination of an optical model like *PV Optics* and PC1D.

Accurate modeling of a polycrystalline TF-Si solar cell is complicated not only because of GB issues but also because of a recently observed phenomenon known as *defect-clustering*. It is observed that polycrystalline Si exhibits segregation of intragrain defects into grains of some specific orientations. Thus, one is able to find grains of zero-defect density adjacent to very heavily defected grains (defect clusters). The formation of defect clusters in polycrystalline Si is attributed to relief of thermal stress (produced during crystal growth or deposition) through dislocation generation by grains having certain preferred orientations. These orientations have the lowest-yield stress for the growth or deposition conditions [67]. When the defects are clustered, it is expected that the potentials introduced by different defects may couple with each other if they are close enough spatially, so that some second-order extra energy levels, or even an energy-band-like structure, will be generated. But, unfortunately, there is so far no study on this subject. As a result, modeling of TF-Si cells must include laterally nonuniform material.

A first-order approximate (but simple to handle) model for a polycrystalline TF-Si solar cell is to regard cell performance as being controlled by the spatial variations arising from changes in the grain-to-grain properties such as dislocation density. Each grain can be assumed to be uniform. In this approximation, one can embed GB effects into lumped series resistance that interconnects various grains through a network model. This model was developed at NREL to predict the effects of spatial nonuniformities in a large-area solar cell [68, 69]. Here, the total cell consists of a parallel combination of a large number of smaller cells (in this case, each cell corresponding to a different grain). The characteristics of each cell are determined by the local properties of that grain.

Figure 8.20 illustrates the network model. The solar cell is divided into an array of diodes, where each diode is small enough to assume a uniform distribution of defects. Each node in the matrix depicts a local cell, connected to other cells by a resistor representing the series resistance. The series resistance arises from a number of sources that include the sheet resistivity of the emitter in an n/p device.