in both initial efficiency and stability. The ability to make high-quality a-Si material at high rate using VHF could be very important for high-throughput manufacturing.

Although the advantages of using VHF deposition for high-rate growth have been clearly demonstrated, VHF process had not yet been used in large-scale production at the time of publication of this book. There are two principal challenges to applying VHF deposition in manufacturing. (1) Nonuniform deposition on a large, production-scale substrate. RF standing waves may be formed on the electrode when the electrode size is comparable to half the wavelength of the RF wave. (2) VHF coupling. It is fairly difficult to couple VHF power from the generator to large electrodes. Several research groups are working in this area and have made significant progress [86].

12.3.3.2 Microwave glow discharge deposition

Glow discharge deposition at a microwave frequency of 2.45 GHz has also been studied [87, 88]; as expected from Figure 12.12, very high deposition rates are obtained. When the MW plasma is in direct contact with the substrate, the deposited films show poor optoelectronic properties compared with RF-deposited films, and are not suitable as intrinsic layers for high-efficiency solar cells. *Remote* MW excitation has also been studied [89], and high-quality films have been obtained. In remote plasma-deposition processes, substrates are placed outside the plasma region. The MW plasma is used to excite or decompose a carrier gas such as He, Ar, or H_2 that passes through the MW zone toward the substrates. The excited carrier gas then excites SiH_4 or Si_2H_6 directed into the chamber near the substrates. Using such an indirect excitation process, the concentration of SiH_3 radicals can be maintained, while the concentrations of other radicals (SiH_2, SiH, etc.) can be minimized. However, the high deposition rate of the direct plasma deposition is also reduced with remote plasmas. MW plasma deposition has been studied at United Solar [90] and Canon [91, 92], and is used for the deposition of some of the i-layers in Canon's 10 MWp triple-junction production line. Generally, the structural and optoelectronic properties of MW-deposited a-Si-based films are poorer than RF-deposited films. However, at a very high deposition rate, for example 50 Å/s, the MW-deposited films will be superior to films made using RF and VHF deposition.

12.3.4 Hot-wire Chemical Vapor Deposition

Several years after Hot-Wire Chemical Vapor Deposition (HWCVD) was introduced [68, 93], Mahan *et al.* [69] improved the deposition process and produced a-Si films with superior material performance. Since then, HWCVD has been studied and used on an experimental scale worldwide for depositing high-quality a-Si- and μc-Si-based films at high rate. The setup for a HWCVD system is similar to the schematic shown in Figure 12.11 for RF-PECVD except that the RF electrode is replaced with a heated filament. In a HW process, SiH_4 gas or a mixture of SiH_4 and other gases such as H_2 or He is directed into the chamber. The gas is catalytically excited or decomposed into radicals or ions by a metal filament heated to a high temperature (around 1800–2000°C). The silicon radicals then diffuse inside the chamber and deposit onto a substrate placed a few centimeters away and heated to an elevated temperature of 150 to 450°C. Mahan *et al.* demonstrated that HWCVD a-Si materials show relatively lower H