# On-Chip Semiconductor Device Impedance Measurements Using the HP 4291B

HEWLETT® PACKARD

## Application Note 1300-7

**HP 4291B RF Impedance/Material Analyzer**

### Introduction

Semiconductor processing technology and device design has advanced rapidly over the past decades. Modern Silicon and GaAs technologies are capable of producing chips operating at frequencies of several GHz or higher, for both analog and digital applications. This trend towards higher operating frequencies introduces the need for techniques to characterize semiconductor devices at similar frequencies. Evaluation of circuit behavior alone will not be sufficient. Analysis of individual devices at high frequencies is essential for device research and device model development, whether it be bipolar or MOS transistors or passive components.

A powerful method to study device behavior at high frequencies is to measure one-port device impedances under different static bias conditions. A wide variety of characterization techniques can be found in the literature, based on this kind of impedance measurements. In the case of MOSFETs, measurement of the small signal drain conductance under various bias conditions provides valuable information on the operation of these devices in high frequency circuits. Analysis of the small signal drain conductance reveals aspects of dynamic MOSFET device behavior that are otherwise difficult to measure, such as impact ionization and self-heating effects. The small signal drain conductance of a MOSFET is typically very small (less than 1 mS). Measurement of such small conductances at high frequencies is extremely difficult, due to the unavoidable presence of parallel capacitances, both in the device and the measurement setup. At high frequencies, these parallel capacitances add a comparatively large imaginary part to the measured impedance. This requires an impedance analyzer capable of resolving very small phase angles, together with very accurate calibration techniques to compensate for the parasitic capacitances in the measurement setup.

Traditionally, impedance measurements are carried out using a Vector Network Analyzer (VNA). However, VNAs typically only measure impedances in a narrow range around 50 Ω,while the device impedance of interest may vary over a very wide range, from less than 1 to more than 1 MΩ. The HP 4291B Impedance/ Material Analyzer offers a solution for the measurement problems outlined above, with an unique combination of a very wide impedance measurement range, a wide DC bias range, advanced calibration and compensation techniques and powerful analysis capabilities.

The most interesting features of the HP 4291B are:

- Frequency range from 1 MHz to 1.8 GHz.
- Internal source for a DC bias up to 40 V or 100 mA.
- Measurement range of 0.1 Ω to 50 kΩ (at 1 MHz and 10% accuracy).
- Direct display of any combination of |Z|, Θ, R, G, X, B, C, or L.
- Compensation of test fixture parasitics.
- Powerful equivalent circuit analysis.

These features make the HP 4291B an ideal instrument for semiconductor device impedance analysis. This application note demonstrates how the HP 4291B can be used for direct on-chip impedance measurements. In particular, the issue of how to connect the sample to the analyzer is addressed. As an example, drain conductance measurements on SOI MOSFETs are discussed. A detailed discussion of the many possible applications of semiconductor impedance measurements is beyond the scope of this note.

## The Test Fixture

There are two basic methods to connect a semiconductor device to an analyzer such as the HP 4291B: direct wafer probing or fixturing. The first solution uses an RF probe which is positioned to contact the relevant pads of the device directly on the wafer. In the letter solution an individual chip is mounted on a test fixture and the relevant device connections are made with bond wires. Both methods have specific advantages and disadvantages. Direct probing allows quick measurements but connection of additional DC biases is difficult. This poses a problem for measurements on devices with more than two terminals. Fixturing provides a very flexible though more cumbersome solution, because the wafer has to be cut and bond wire connections have to be made. Because of its flexibility, a test fixture solution is presented in this application note.

A test fixture solution for use with the HP 4291B for an arbitrary semiconductor device has to meet the following requirements:

- Short electrical length together with very low reflection and loss for frequencies up to 1.8 GHz, to allow measurements of high impedance without excessive phase shift or loss of accuracy.
- RF connections capable of supporting a DC bias of up to 40 V or 100 mA.
- Chip mounting area sufficiently big to accommodate commonly used test chip sizes, and preferably isolated from the measurement ground plane to allow a separate DC substrate bias.

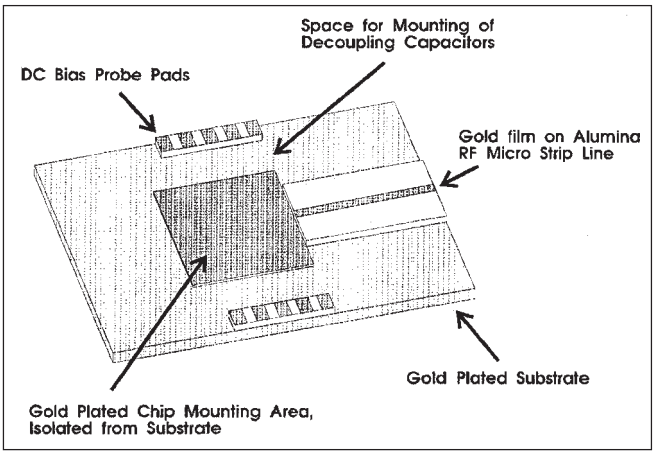


**Figure 1. The RF chip carrier solution for use with the HP 4291B.**

- A facility to connect external DC biases for other device terminals and sufficient space to add decoupling for these bias connections.
- Calibration standards to compensate test fixture parasitics.
- An easy method to charge the chip or device under test (DUT).
- Direct connection to the HP 4291B via an APC-7 connector.

To meet all these requirements, a fixture solution has been especially developed by Inter-Continental Microwave (Santa Clara, CA) and the Southampton University Microelectronics Center (United Kingdom ). In this solution the DUT is mounted on an RF chip carrier as shown in Figure 1. The chip mounting area allows chip sizes up to 7 mm square and is isolated from the carrier substrate by a thin low-loss dielectric. The RF connection to the HP 4291B is made through a micro stripline. The chip carrier provides probing pads to connect up to 10 external DC biases and sufficient space to mount decoupling for these bias connections on the carrier substrate.

All connections can be made with standard wire bond techniques. The test chip has to be mounted with the DUT as close as possible to the edge of the micro stripline to keep the RF bond wire connection as sort as possible, though several millimeters of bond wire is acceptable at frequencies up to 1.8 GHz. When all required connection to the DUT are established, the RF chip carrier is placed in a test fixture. This fixture connects directly to the APC-7 connector on the test head of the 4291B. Figure 2 shows a photograph of the test fixture and the RF chip carriers. The total electrical length of the test fixture including the micro stripline on the chip carrier is as short as 28.2 mm. At 1.8 GHz the loss in the fixture with chip carrier is only -0.2 dB and the reflection is better than -48 dB.

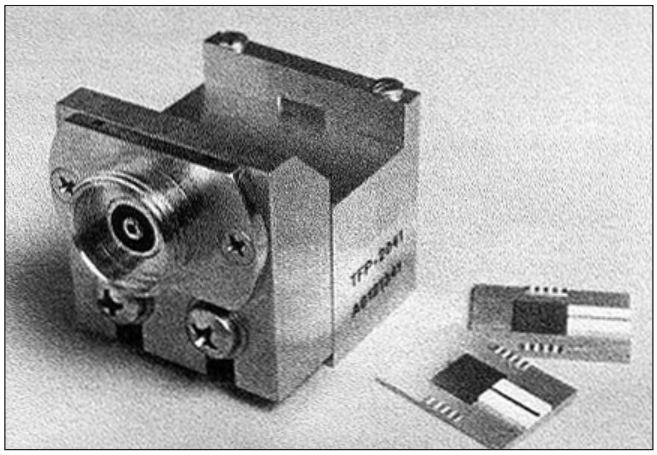

**Figure 2. The Inter-Continental Microwave test fixture and chip carriers**

## Calibration and Compensation

The HP 4291B uses both calibration and compensation techniques to improve the accuracy of measurements. Calibration is performed first, using the SHORT, OPEN, LOAD, and LOW LOSS CAPACITOR calibration standards supplied with the HP 4291B. This calibration sets an accurate reference plane for all measurements at the edge of the APC-7 connector on the test head, Compensation, on the other hand, is used to compensate for the parasitic impedance of the test fixture used during the measurement. The HP 4291B allows two different compensation techniques, depending on how the parasitic phase shift is calculated. Fixture compensation can be performed with either OPEN and SHORT calibration standards together with a separately specified electrical test fixture length or with OPEN, SHORT, and LOAD calibration standards. For the ICM test fixture OPEN and SHORT calibration standards are available, consisting of an "open" and a "closed" micro stripline equivalent to the striplines used on the RF chip carriers. The fixture compensation using these calibration standards thus moves the effective reference plane for the measurement with the fixture from the APC-7 connector of the HP 4291B test head to the edge of the micro stripline on the chip carriers.

For accurate measurements it is strongly recommended that both calibration and fixture compensation are performed in USER mode rather than FIXED mode. In USER mode the calibration and compensation data are measured at identical frequencies and oscillation levels as will be used during the measurement, rather than estimated by interpolation. The POINT AVERAGE FACTOR should be set to a minimum of 8 during calibration and compensation.

To illustrate the effectiveness of SHORT/OPEN/LENGTH fixture compensation using the ICM calibration standard, Figure 3 shows the measured impedance of a 150 Ω Solution Microwave Chip Resistor after fixture compensation in USER mode. This type of resistor consists of a thin NiCr film on an alumina substrate and has a maximum operating frequency well above 1.8 GHz. The resistor is mounted on one of the RF chip carriers and connected to the micro stripline with a 2 mm bond-wire and to the carrier substrate (ground plane) with a 4 mm bond wire. The measurement error at 1.8 GHz is less than 5%. It should be noted that this measurement is still influenced by the parasitic series inductance of the bond wires and the parasitic parallel capacitance of the bonding pads of the resistor. The equivalent circuit analysis capabilities of the HP 4291B can be used to estimate these parasitics. Values for the parallel capacitance and series inductance of 64 fF and 3.1 nH respectively are found. The dashed line in Figure 3 shows the impedance of the equivalent circuit simulated by the HP 4291B.

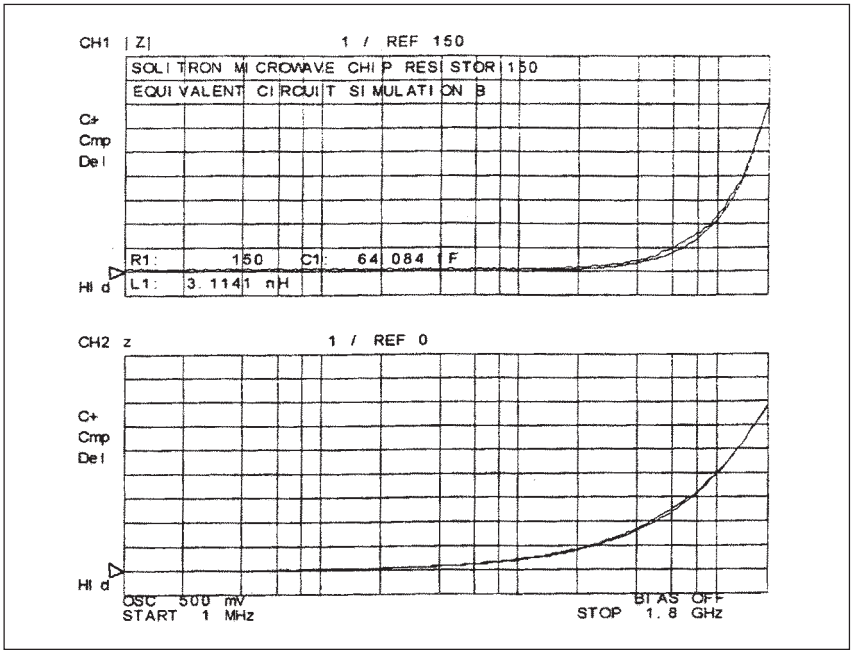


**Figure 3. Measured impedance of a 150 Ω Microwave Chip Resistor after SHORT/OPEN/LENGTH fixture compensation (solid line) and simulated equivalent circuit impedance (dashed line).**

Very good agreement is achieved between the simulated and the measured impedance characteristics.

The ICM calibration standard available for the fixture discussed here provides a convenient and accurate method to perform fixture compensation. However, when on-chip SHORT, OPEN and LOAD calibration standards are available, it is possible to compensate accurately not only for the parasitic impedance of the fixture and the micro stripline, but also those of the bond wires and bonding pads. These calibration standards would have to be included in the design of a test chip to match the DUT.

## DC Bias and Decoupling

When measuring one-port impedances on semiconductor devices with more than two terminals, it is often required that DC biases are applied to the other device terminals to set the appropriate operating point. Whilst the HP 4291B optionally supplies a DC bias to the RF measurement terminals, DC biases for the other device terminals will have to be supplied using external sources. Furthermore, decoupling capacitors have to be connected between these other DUT terminals and the measurement ground plane, to ensure that the bias on these terminals is truly static and not influenced by the high frequency measurement (due to internal coupling in the device). It is essential that this decoupling is placed as close as possible to the DUT. One of the advantages of the test fixture solution presented here is the facility to connect external

static biases. The chip carriers for the ICM test fixture have ten probing pads available for this purpose. Sufficient space is available to mount decoupling directly on the chip carrier, between the DUT and the DC probing pads, thus minimizing the required connections.

The only problem that needs to be addressed by the user of the test fixture is how to connect an external DC bias supply to the probing pads on the chip carrier. Because the probing pads are relatively large (several square millimeters) many simple solutions are feasible. Further, because the high frequency decoupling is mounted on the chip carrier, the connections between the DC probing pads and the external bias supply are true DC connections and will not influence the RF impedance measurement, whichever solution is chosen. This greatly simplifies the problem. The simplest solution would be to solder directly a small wire onto the probing pads. A more flexible solution would be to mount one or more standard DC needle probe positioners on the test fixture. A wide variety of DC needle probes is available from many manufactures. Depending on the design of the needle probes used, the required mounting bracket can be quite simple. Figure 4 shows a possible solution, using two Karl & Suss needle probes mounted on the side of the ICM test fixture.

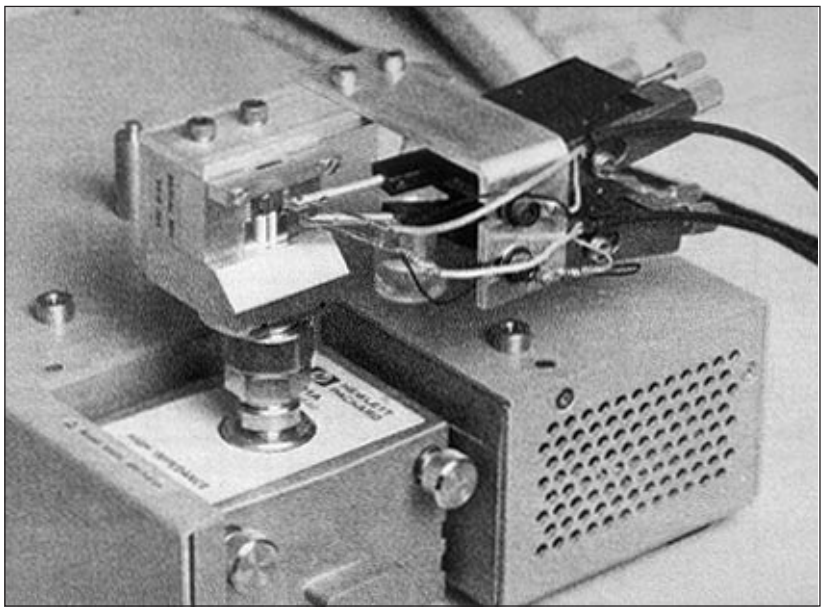

**Figure 4. The ICM fixture together with two DC probes mounted on the HP 4291B test head.**

It is difficult to give general guidelines for the amount of decoupling required for the DC bias connections, as this strongly depends on the characteristics of the DUT. However, in most cases a single decoupling capacitor in the order of 1 nF will be adequate. The decoupling capacitors used must be suitable for operation at frequencies up to 1.8 GHz and small enough to fit on the chip carrier. Thin Film Microwave Capacitors are ideal for this purpose and generally available, for instance, from Electro-Films (Warwick, RI). There is a small possibility that the needle probes or wires used to connect external DC biases to the chip carrier cause resonances at frequencies within the range of the HP 4291B. In this case it may be required to use a more complex decoupling network, with more than one decoupling capacitor and a small resistor in series with the bias connection to damp the resonance.

## An Example— SOI MOSFET Drain Conductance Measurements

To demonstrate the use of the HP 4291B together with the ICM test fixture and external DC biasing in a practical application, some drain conductance measurements on Silicon-On-Insulator (SOI) MOSFETs are discussed in this section.

Many analog circuits, and to a lesser extent digital circuits, in CMOS technology rely on the assumption that the drain conductance in the saturation region is constant. However, in SOI MOSFETs the drain conductance in the saturation region may be influenced by several parasitic effects such as the kink effect, bipolar transistor action and self heating. These parasitic effects are strongly frequency dependent. The kink effect does not influence the drain conductance at high frequencies.

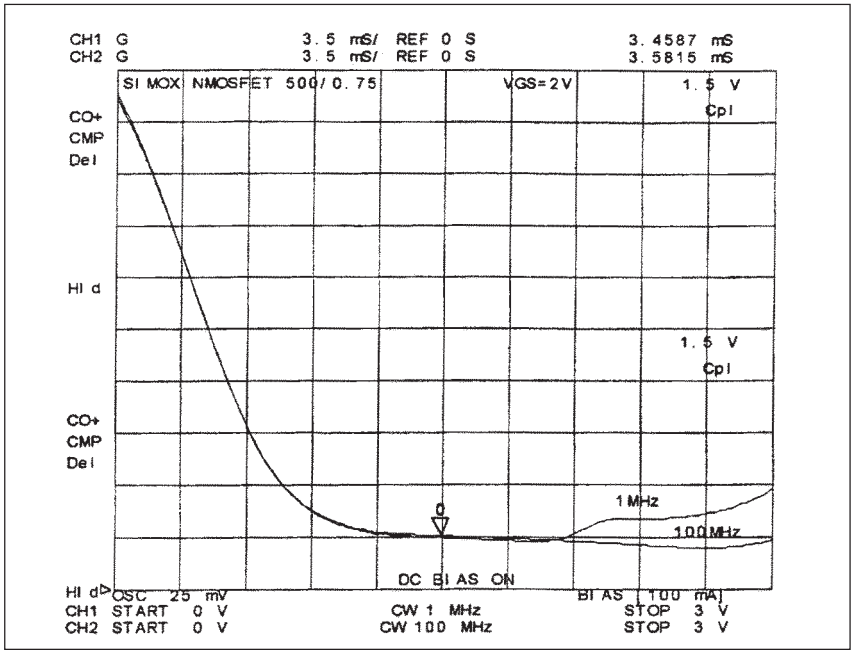


**Figure 5. Drain conductance versus drain bias for two different frequencies.**

The influence of dynamic device self heating is also strongly reduced at high operating frequencies, as the device reaches a constant temperature. To allow confident circuit design in SOI CMOS technologies, these effects need to be accurately characterized for all possible operating frequencies. Some of the frequency dependent effects are only apparent at higher frequencies. For instance, the time constants associated with dynamic self heating are typically in the order of 1 µs or shorter. Thus measurements at frequencies in the MHz range or higher are required to characterize this effect.

For the experiment described here, an n-channel SOI MOSFET with gate dimensions of 500 × 0.75 µm, fabricated on a SIMOX wafer, was selected. The device is mounted on an ICM chip carrier and all required connections are made with 0.25 µm gold bond wire. The source is connected to the ground plane (carrier substrate), the drain to the micro stripline, and the gate is connected to one of the DC probing pads. A single 1 nF thin film capacitor is mounted on the chip carrier for the decoupling of the DC bias for the gate. The substrate of the DUT is connected to the ground plane for this measurement. In this configuration, the HP 4291B is used to measure the drain conductance and simultaneously supply the DC drain bias. A separate voltage source is used to supply the gate bias.

The oscillation level of the HP 4291B is set to 25 mV to approximate a small signal measurement. The analyzer is calibrated and fixture compensation is performed using the ICM calibration standards.

Figure 5 shows the measured drain conductance during a drain bias sweep at two different frequencies and with a gate bias of 2 V. This measurement uses the capability of the HP 4291B to set different measurement parameters for the two measurement channels, to allow easy comparison of bias sweep measurements at different frequencies. This graph clearly shows that the kink effect still influences the dynamic drain conductance of this MOSFET at 1 MHz but no longer at 100 MHz.

A convenient method to study the influence of self heating in a MOSFET is to measure the drain conductance for different frequencies at a point in the saturation region but before the onset of the kink effect. Because the two measurement channels of the HP 4291B can be used to sweep different variables, this complex measurement is made much easier. This is demonstrated in Figure 6. The first measurement channel is used to sweep the drain bias and the marker is used to determine quickly a suitable point in the saturation region. The parameters for the second measurement channel are then set to sweep simultaneously the frequency at this bias point.

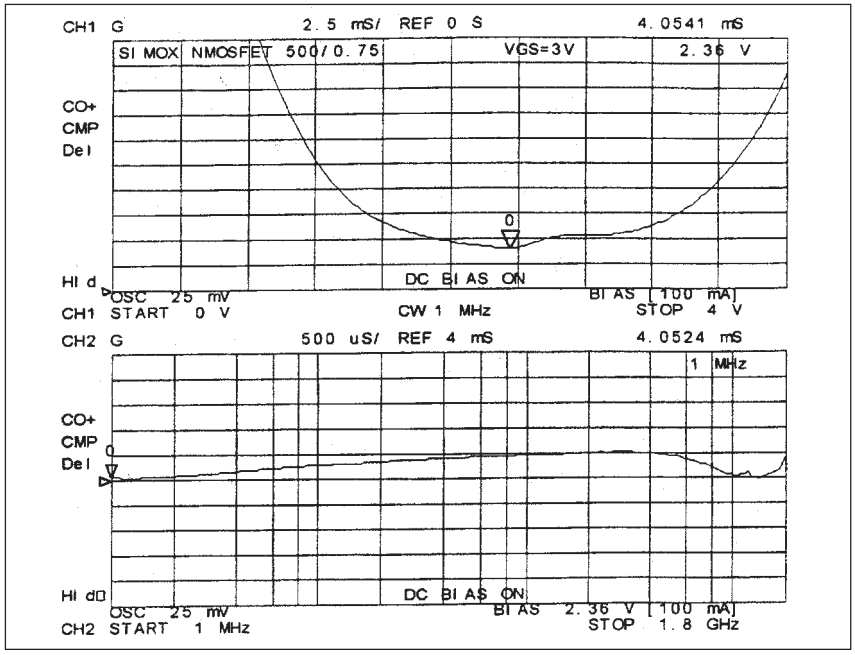


**Figure 6. Drain conductance versus drain bias and versus frequency in one measurement.**

It can be shown that a combination of static and high frequency measurements of the drain conductance at identical bias conditions can be used to calculate directly the first order thermal resistance of the MOSFET. This is a relatively simple technique. Extraction of the device thermal resistance otherwise requires special test structures and measurements at different temperatures. A detailed discussion of this technique is beyond the scope of this application note. However, it provides a good example of one of the interesting applications of one-port RF semiconductor impedance measurements. More information on the analysis of drain conductance measurements on SOI MOSFETs can be found in the following references:


- W. Redman-White, M.S.L. Lee, B.M. Tenbroek, M.J. Uren and R.J.T. Bunyan, "Direct Extraction of MOSFET Dynamic Thermal Characteristics From Standard Transistor Structures Using Small Signal Measurements," *Electronics Letters*, vol. 29, no. 13, pp. 1180--1181, 24th June 1993.

- B.M.Tenbroek, W.Redman-White, M.J. Uren and M.C.L. Ward, "Identification of Thermal and Electrical Time Constants in SOI MOSFETs from Small Signal Measurements," in *Proceedings of the 23rd European Solid State Device Research Conference*, (Grenoble, France), pp. 189--192, September 1993.

- M.S.L.Lee, W. Redman-White, B.M.Tenbroek and M. Robinson, "Modelling of Thin Film SOI Devices for Circuit Simulation including Per-Instance Dynamic Self-Heating Effects, "in *Proceedings IEEE International SOI Conference*, (Palm Springs, California, USA), pp.150-151, October 1993.

## Conclusion

With its wide impedance measurement range, internal DC bias supply and powerful analysis capabilities, the HP 4291B RF Impedance/Material Analyzer is a very suitable instrument for semiconductor impedance measurements. The test fixture solution presented in this document provides a flexible and accurate method to connect test chips to the HP 4291B with optional external DC biasing and the availability of calibration standards. Together, an advanced system is established for accurate on-chip semiconductor device impedance measurements in the frequency range of 1 MHz to 1.8 GHz, allowing a variety of interesting applications.

## Recommended List of System Components

- Hewlett-Packard HP 4291B impedance/Material Analyzer with High Impedance Test Head and DC Bias Option 001.
- ICM Test Fixture TFP-2041 (supplied by Inter Continental Microwave, Santa Clara, CA, part number A0121341)
- ICM Chip Carrier Assemblies (supplied by ICM, part number A0121254A)
- ICM Calibration Standard (supplied by ICM, part number A0121255)
- Standard DC needle probes and positioners (optional, for example Karl & Suss)
- Custom mounting bracket for DC probes (optional)
- Thin film Microwave Capacitors for decoupling (optional supplied by Electro-Films, Warwick, RI)
- Microwave Chip Resistors for decoupling (optional, supplied by Solitron, West Palm Beach, FL)
- Microwave Chip Resistors for decoupling (optional, supplied by Solitron, West Palm Beach, FL)

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**Latin America:**
Hewlett-Packard
Latin American Region Headquarters
5200 Blue Lagoon Drive
9th Floor
Miami, Florida 33126
U.S.A.
Tel: (305) 267-4245
(305) 267-4220
Fax:(305) 267-4288

**Australia/New Zealand:**
Hewlett-Packard Australia Ltd.
31-41 Joseph Street
Blackburn, Victoria 3130
Australia
Tel: 1 800 629 485 (Australia)
0800 738 378 (New Zealand)
Fax:(61 3) 9210 5489

**Asia Pacific:**
Hewlett-Packard Asia Pacific Ltd.
17-21/F Shell Tower, Times Square,
1 Matheson Street, Causeway Bay,
Hong Kong
Tel: (852) 2599 7777
Fax:(852) 2506 9285


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