A Local Area Network Laboratory Based on the Keithley 4200-SCS for Engineering Education in Microelectronics

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Introduction

The microelectronics laboratory has been an integral part of the modern curriculum in engineering education for years so that undergraduate students can apply what they've learned of their device physics and VLSI courses. In this way, they can perform measurements on "home-made" devices and/ or advanced devices imported from the industry in the framework of an end-year project. The continuous progress in microelectronics technology has largely replaced the classic curve-tracer with a modern PC-controllable parameter analyzer, allowing students to make more precise and convenient measurements.

However, due to the relative high cost of this type of equipment, equipping a teaching lab with many such measurement units may be unaffordable. As a result, during the last decade, the concept of a remote laboratory through the Internet has been pioneered at Rensselaer Polytechnic Institute [1, 2] (AIM-Lab) in collaboration with the Norwegian University of Science and Technology [3] (Lab-On-Web) and developed at MIT [1, 4] (Web Lab) to allow a large numbers of users to share a single piece of advanced equipment from their home or any other location in the world. The limits of this approach are, of course, due to the elimination of the "hands-on" experiments in a lab environment: lack of flexibility (changing the device, changing the instruments, degree of programming flexibility, etc.), but also lack of immediate feedback from the system itself (precision of the manual probe setup, observation of instruments and devices, human environment, etc.), and, last but not least,

the lack of good laboratory practices (note-taking, discipline, troubleshooting, personal initiative, and instructor guidance, etc.).

The concept presented here offers a compromise solution. It allows students in the lab framework to measure several devices mounted on separate probe stations respectively. These stations are connected to a state-of-art Keithley Instruments Semiconductor Characterization System (4200-SCS) and other instruments (C-V meters, pulse generators, etc.) through a switch matrix. A PC located beside each station allows students to access the 4200-SCS remotely for measurements through the Local Area Network (LAN). The concept, named Lab-e-LAN, was originally designed, set up, and successfully run at Bar-Ilan University's School of Engineering (Israel) for the last two academic years; it was also imported to the Hebrew University of Jerusalem's School of Engineering (Israel) in 2006.

Lab-e-LAN purposes and architecture

The Advanced Device Characterization Lab is intended for the fourth-year undergraduate students in the microelectronics track. Twelve three-hour lab sessions are scheduled over the second semester. The lab present capacity is three pairs of students at a time and is expandable to six pairs or more. In addition to its use as a teaching lab, the lab allows students to pursue advanced end-year projects in microelectronics (described below) and also will serve some research projects in prototype device testing and reliability studies (in development).

The Lab-e-LAN lab architecture is summarized in *Figure 1*. The Keithley 4200-SCS is the core of the lab and was specially selected to fit into the LAN concept thanks to its embedded industrial PC (Pentium 4) and the powerful Keithley Interactive Test Environment (KITE) software, which runs under the Windows XP environment. An incremental point was that Keithley released a "PC or off-line version" of KITE, which allows the user to define the test and analyze the data from his or her own PC without actually being connected to the 4200-SCS. A LAN connection is then established from the user's PC using the Windows Remote Desktop software, for example. In this way, each user is typically connected to the 4200-SCS for less than one minute, which is all the time needed for file opening, data acquisition, and saving the results (see the lab protocol described later). Connections between the 4200-SCS and the other rack-mounted instruments to the switch matrix are made through triax cables (using the guard potential method [5]).
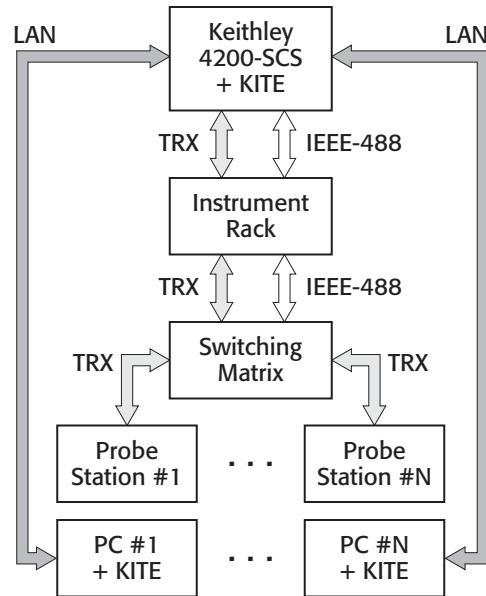
Figure 1: The LAB-e-LAN architectural concept and connections type (TRX=triax cable)

Lab-e-LAN Equipment

In the present configuration in Bar-Ilan University's lab, three pairs of students can work in a same lab session, sharing two different probe stations and one test fixture respectively. The following instruments can be used on each probe station through the switch matrix:

1. *Measurement instruments (rack-mounted)*

   - Keithley Model 4200 Semiconductor Characterization System equipped with three medium-power (220V max, 1A max) Source-Measure Units. External flat screen.

   - Keithley Model 590 C-V Analyzer: Dual frequency 100kHz/1MHz.

   - Keithley Model 595 Quasistatic C-V meter.

   - Keithley 3402 R Dual-Channel Pulse Generator (recently installed).

   - Keithley Model 707A Switch Chassis: Allows insertion of up to six matrix cards.

   - Keithley Model 7072 Switch Matrix Card (8 inputs × 12 outputs) designed for semiconductor measurements (One card in the present configuration).

The Keithley 4200-SCS and the lab instruments are connected to the input ports of the switch matrix through triax and IEEE-488 cables, as shown in *Figure 2*.
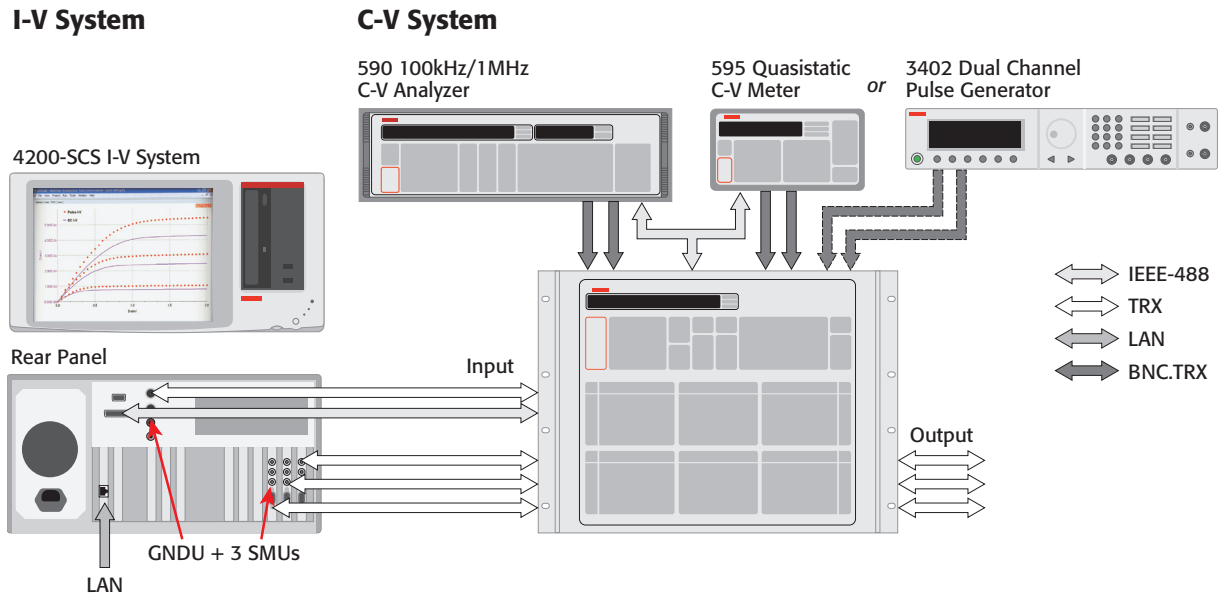
I-V System

C-V System

590 100kHz/1MHz
C-V Analyzer

595 Quasistatic
C-V Meter   *or*

3402 Dual Channel
Pulse Generator

4200-SCS I-V System

Rear Panel

Input

IEEE-488

TRX

LAN

BNC.TRX

Output

GNDU + 3 SMUs

LAN

Figure 2: Diagram of the lab instruments connected to the switch matrix.

2. *Probe Stations*

   The Keithley 4200-SCS and the lab instruments (I-V/C-V central system) are connected to the input ports of the switch matrix through triax cables, as shown in *Figure 3*. The following probe stations are connected to the matrix output ports:

   • **Rucker and Kolls 660J manual probe station** (in a dark box). This station can be used to probe chip samples and wafers up to six inches in diameter and is equipped with a Bausch and Lomb long distance microscope (objective ×10, ×40) and eyepieces (×10). The probes hold four micromanipulators (Quater Research XYZ-300 T). Pads as small as 10μm can be probed.

   • **MDC 490 QuietCHUCK DC Hot Chuck System** (in a dark box). This station can be used to probe chip samples and wafers up to eight inches in diameter and is equipped with a Leica G6ZT binocular microscope (×4–×10) and eyepieces (×10). It can support up to six micromanipulators (Quarter Research XYZ-300 T). Pads as small as 100μm can be probed. The chuck can be heated up to 350°C using a digital controller and cooled down using a dedicated chiller. A light bulb inside the box can be operated manually for evaluating the effects of illumination on semiconductor devices.

- **Keithley 8006 Test Fixture.** Users of this station can probe packaged devices (TO, DIP 28 pins, etc.) in quiet conditions (dark box, mini-triax connections, etc.) by just plugging them onto the test board and connecting them to the rear triax/BNC connectors pad using mini cables.
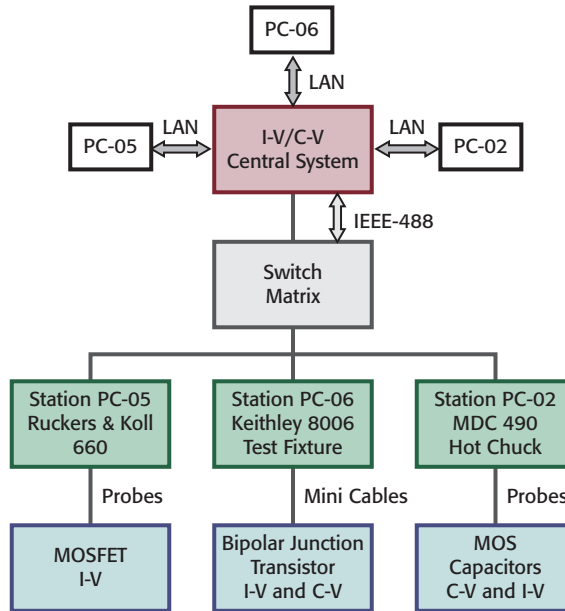

Figure 3: Schematic diagram of the LAB-e-LAN.

The switch matrix card is configured as shown in *Figure 4*. The Model 3402 pulse generator replaces the Quasistatic C-V meter when necessary.
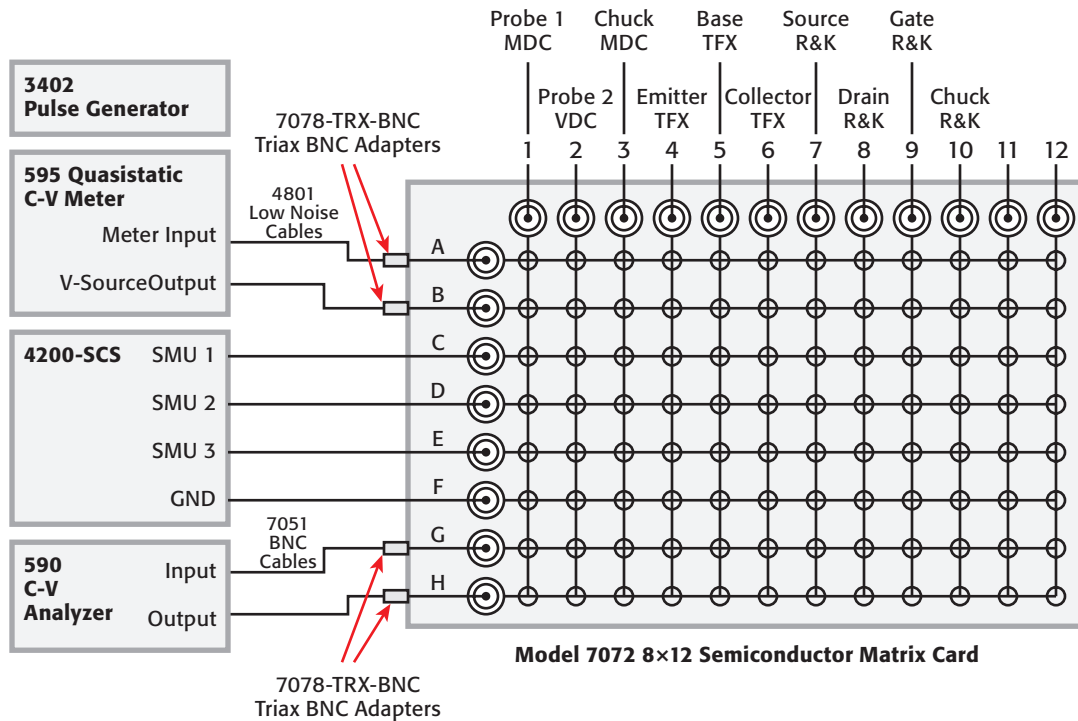
Figure 4: Configuration of the Keithley Model 7072 Semiconductor Matrix Card used to connect the instruments to the probe stations.

LAB-e-LAN Protocol

The data acquisition protocol is quite straightforward:

1. After running the KITE software version ("off-line") from his PC station, the user opens an existing project file located in a predefined library corresponding to his current experiment or device (e.g., MOSFET). Typically, the project file contains a User Test Module (UTM), which defines the matrix pin connections from the instruments to the current probe station. A subsequent Interactive Test Module (ITM) defines one experimental setup (e.g., Id-Vd, Id-Vg, etc.), which is provided to the student via a user-friendly Graphic User Interface (GUI). Additional experimental set-ups can be added in a sequence.

2. After completing the setup, the project file is saved and closed.

3. Then, the user runs remote control software from his or her PC (such as Windows Remote Desktop) to access the 4200-SCS through the LAN connection. A password is required to access the system remotely and to identify the user (access tracking can be performed in the background).

4. After running the full KITE software located in the 4200-SCS remotely, the user opens the project file located on his or her own PC and executes it via the LAN connection.

5. Within less than a minute (typical), a real-time plot of the data acquired is displayed on the screen. After checking the plot for coherence, the user saves and closes the project file before logging off. Interference of other users is avoided by setting a warning message in the remote software. Then, the system is available for further connection.

6. Back at the PC station, the user reopens his project file and can perform all the necessary data processing and graph editing "off-line"

Teaching Topics

Three topics are covered in the microelectronics teaching lab using the 4200-SCS in its present configuration. In the future, more topics will be developed in a modular fashion. Each topic is divided in two parts and scheduled to take up three lab sessions. The lab assignments are available for the students on-line through the Bar-Ilan University *hi-learn* [6] website and the Hebrew University website [7]. Lab reports are collected by e-mail. In this way, the LAB-e-LAN adheres to a "zero paper" policy. The reference literature is available at the lab and campus library. Students are encouraged to use extensively the reference books [8-11].

1. *MOS Capacitors*

   The samples are processed at the Microelectronics Lab of the Hebrew University of Jerusalem. One silicon wafer [n-type (Phosphor), range ~1–10Ω-cm] with (100) orientation and two other wafers but with (111) orientation are oxidized (wet) to produce a oxide thickness of a few hundred nanometers. Then, an aluminum layer is evaporated through a mechanical mask, which defines the shape and area of the capacitors (10^{-2} to 10^{-3}cm^2). Subsequent annealing in forming gas (H_2:N_2) is performed except for one of the Si(111) wafer. The wafers are probed on the MDC 490 Quiet CHUCK DC Hot Chuck System under software control. Device parameters are extracted from the C-V and I-V measurement results as follows:

Part	Topics
A **Basic level**	• C-V curves (High Frequency: **100kHz**): Doping type – Oxide thickness – Flatband voltage – Threshold voltage – Bulk doping – Maximum Depletion Width – Sensitivity of the inversion layer to equilibrium: voltage sweep rate and direction – Light and temperature effects.
	• I-V curve: charge built up (measure V-Time plot with low I sourcing). Oxide capacitance determination. Comparison with C-V curves.
B **Advanced level**	• **C-V curve (Quasistatic)** combined with C-V curves: Surface potential ψ_s as function of the applied voltage – Interface states density D_{it} =f(ψ_s) of Si(100) compared to Si(111): influence of orientation and post processing annealing.
	• **C-V curves (High Frequency: 100kHz):** Mobile oxide charge density (Bias Temperature Stress: 200°C, 10 min, ±10V)

2. *Bipolar Junction Transistor*

For this topic, the sample is the classical silicon bipolar junction transistor NPN 2N2222A, packaged in a TO-8 case. The device is probed using the Keithley Model 8006 Test Fixture. Device parameters are extracted from C-V and I-V measurements as follows:

Part	Topics
A	• Forward Common Emitter output characteristics: Ic=f(Vce>0,Ib), Iceo(f) measurement.
	• Forward CE input characteristics: Ib = f(Vbe) for several Vce positive values.
	• Forward Gummel plot: log Ic, log Ib = f(Vbe >0).
	• Gains βf = Ic/Ib and αf determination.
	• βf as function of log(Ic): low and high injection effects.
	• **Non ideal characteristics:** Early Voltage.
B	• Reverse CE output characteristics: Ic=f(Vce<0,Ib), Iceo(r).
	• Reverse CE transfer characteristics: Ib=f(Vbe) for several Vce negative values.
	• Reverse Gummel plot: logIe, logIb=f(Vbc>0).
	• Gains βr = Ie/Ib and αr determination.
	• βr function of log(Ie): low and high injection effects.
	• Vce(sat) = Vbe(on) – Vbc(on) determination for a given Ib current.
	• Ebers Moll model building and comparison to experiment.
	• C-V characteristics of the BE and CE junctions. Base doping concentration.

3. *Sub-micron integrated MOSFET*

The device is a modern research FET based on a 0.5µm CMOS technology (channel designed length). Channel width (W) is 50µm. The gate oxide thickness is 11.5nm. The oxide gate is connected through a N+ polysilicon layer. Device parameters are extracted from I-V measurements as follows:

Part	Topics
A **Basics and short channel effects**	• Output characteristics: $I_{DS} = f(V_{DS},V_{GS})$: Type of p-MOSFET (enhancement or depletion), Channel Length Modulation parameter (λ) Effective channel length as function of V_{DS} in the saturation region (V_{DS}<–3V)
	• Transfer characteristics: $I_{DS} = f(V_{GS})$ and Transconductance g_m = f(V_{GS}) in the linear region (V_{DS} = –0.1V): Determination of the threshold voltage V_T and of the transconductance factor k. Derivation of the effective channel mobility μ_{eff} as function of V_{GS}.
	• Body Bias characteristics: $I_{DS} = f(V_{GS},V_{BS}>0)$, determination of the γ factor in the linear region (V_{DS} = –0.1V). Doping concentration substrate.
B **High field effects**	• Subthreshold characteristics: log(Ids)=f(Vgs) for several high Vds values: Drain Induced Barrier Lowering (Vt shift) effect.
	• Substrate current characteristics: log(Ibs)=f(Vgs) for several high Vds values: Hot carrier injection effects. Incidence on output characteristics at high drain levels.
	• Model of output characteristics using long channel and short channel equations: comparison to experiments.

Conclusions and future plans

The LAN-oriented lab allows direct observation and hands-on experiments with real-world devices and instrumentation (not just simulated or "push-button" experiments), thereby giving the students a more real-life perspective on the field and giving them an opportunity to learn good engineering practices and troubleshooting.

The Keithley 4200-SCS's hardware and software modularity means that the whole lab is working within the same software environment and eliminates the need for a dedicated server to access the instruments or any unusual data acquisition/analysis software. The equipment's versatility allows it to address a broad spectrum of devices and characterization techniques. Therefore, when compared with other characterization solutions, even Keithley's Series 2400 SourceMeter® instruments [12, 13], the concept presented here offers overwhelming advantages.

Finally, experiencing this new high-tech lab created a great deal of interest from the students. Although a bit of patience and giving concessions has been required, as might be expected when so many are sharing the equipment, the students provided positive feedback on the concept.

For the future, we have the flexibility to enlarge the lab's capacity to cover additional topics while using the present configuration by simply adding another Model 7072switch matrix card to the Model 707A Switch Mainframe. For instance, we foresee implementing integrated Schottky and PN diodes on another probe station and a JFET device on the present text fixture or an additional one.

Concerning research topics, we may start some reliability experiments on NROM flash memory devices by cycling the writing/erasing modes using the Model 3402 Pulse/Pattern Generator. The pulse generator unit's (PGU) driver is currently under development to integrate it into the KITE software as a User Test Module. Finally, the LAB-e-LAN could also be made accessible via Web-Lab if we decide it would be beneficial to share the characterization lab's capabilities with external users.

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