A Fully Digital Controlled Off-Chip I_{DDQ} Measurement Unit

B. Straka, H. Manhaeve[*], J. Vanneuville[*], M. Svajda[**]

CEDO, Videnska 127, 61900 Brno, Czech Republic
Phone/Fax : +420 5 4321 4089, E-mail : straka@cedo.cz
[*] KHBO, Microelectronics Department, Zeedijk 101, B-8400 Oostende, Belgium
Phone : +32 59 508996, Fax : +32 59 704215, E-mail : manhaeve@micro.khbo.be
[**] Technical University of Brno, Dept. of Microelectronics, Udolni 53, 602 00 Brno, Czech Republic
Phone : +420 5 41 211 690, Fax : +420 5 43 167 298, E-mail : svajda@umel.fee.vutbr.cz

Abstract

The paper describes a new Digital controlled Off-Chip I_{DDQ} Measurement Unit (DOCIMU), which provides reliable precision and relatively fast measurements, even with a high capacitive load, while the Device Under Test (DUT) is unaffected. The maximal resolution is 50nA and the accurate measurement range is 1mA. Unlike other I_{DDQ} monitors, the DOCIMU copes with external interference, as it needs no analogue pin to set the I_{DDQ} limit and the noise at the V_{DD} is eliminated via a special S/H feature. The DOCIMU is also a testable I_{DDQ} monitor, which is another unique feature.

Keywords:

iddq, iddq monitors, testability, CMOS, integrated circuits, test hardware

1. Introduction

During the last decade, I_{DDQ} testing is being recognised as an important additional test method in order to achieve better quality and reliability. It is well known that excessive quiescent supply current in CMOS ICs identifies a possible failure or a reliability problem. From the technical point of view, the main issue of I_{DDQ} testing is the I_{DDQ} measurement itself. The measurement is mostly done using dedicated circuits: I_{DDQ} monitors/sensors. An I_{DDQ} monitor is called an 'on-chip monitor', if the sensor is integrated together with the other circuitry, while 'off-chip monitors' are inserted in the supply line outside the chip. Whether I_{DDQ} is measured internally or externally, the normal operation of the DUT should not be affected by using a monitor. In addition, the monitor should be fast enough, reliable and accurate to be really applicable in an engineering/production testing environment. On-chip monitors are mostly simple structures. They are generally more sensitive and faster than off-chip monitors, because they are integrated on the chip and they do not drive any decoupling capacitance [1,3,4,12,20,21]. However supply voltage drop and extra delay must be considered in the design. On the other hand, off-chip monitors do not require extra silicon and pins, they are versatile and therefore preferred by IC producers.

The existing off-chip monitors [5,6,7,14,16,17] are mostly semidigital monitors. Some monitors ignore the essential decoupling rules [11,15,19] especially those based on the Keating-Meyer principle. The decoupling capacitor(s) must be placed very close to DUT's supply pin(s). If any switch (relay, MOSFET) is inserted between supply pin and the capacitor, it will add a certain series resistance and inductance and the decoupling will loose its effect. Therefore, the decoupling capacitor(s) should be connected permanently to DUT's supply pin(s) to really cover the transient peaks. Naturally, the decoupling capacitance present limits the speed of the I_{DDQ} testing. However reliability and repeatability has a higher priority than speed in the production testing. The Industry reports that a few hundred/thousand test-vectors are sufficient for a reasonable fault coverage even for large chips [18]. From this point of view, it seems useless to attempt speeds over 100kHz, if proper decoupling is to be sacrificed.

It is not a real issue to design an I_{DDQ} monitor, which works well in an ideal 'laboratory' environment under exactly specified conditions. However, every monitor is a sensitive device and problems will occur as soon as it is put in noisy 'industrial' environment. Hence a good monitor should be designed with regard to EMC, considering noisy/rippled supplies, interference etc. This requires new design approaches and techniques.

2. Description of the DOCIMU

2.1. General description of the DOCIMU

A new testable fully Digital Off-Chip I_{DDQ} Measurement Unit (DOCIMU) was developed to measure the quiescent supply current of digital as well as analogue ICs. The DOCIMU was optimised to drive also heavy capacitive loads, which enables its use also for complex ASICs with multiple supply pins. The monitor provides I_{DDQ} measurements at a relatively high test-speed, up to 30kHz. The DOCIMU exhibits a maximal resolution of 50nA. The operation of the DUT is not affected, as the monitor causes only a neglectable voltage drop (mV). The monitor is intended to be integrated in the test-head of standard automated test equipment (ATE), so it can be used to do I_{DDQ} measurements of packed chips as well as of dies on wafers.

The DOCIMU belongs to the class of ‘fully digital monitors’ according to the QTAG terminology, it also keeps back-compatibility with QTAG semidigital monitors [8,9,13]. Only digital ATE pins are needed to control all the functions of such a digital monitor, in contrast to semi-digital monitors, which require also analogue ATE pin(s).

The DOCIMU is designed to be inserted between the V_{DD} and the supply pin of DUT like an ordinary ampmeter. The DUT is supplied from the V_{DD} supply (provided by ATE) through the monitor. Such a configuration with common V_{SS} (ground) is mostly better than the configuration with a virtual ground because of the sensitivity for possible external interference and the availability of a hard reference.

The DOCIMU has 3 digital control pins (MODE, I/O, CLK), which interface to the ATE, 2 supply pins (+15V, -15V), and 2 I_{DDQ} current-path pins (V_{DD}, DUT) as shown in figure 1. MODE is an asynchronous digital input controlling the measurement cycle. I/O is a bi-directional pin, which acts as data output or data input clocked by the CLK pin with a maximal frequency of 10MHz. The DOCIMU also provides 1 analogue input ($V_{PASS/FAIL}$), 1 analogue output (V_{IDDQ}) to keep it compatible with semidigital monitors. These 2 analogue pins are optional and they are normally not used, since the DOCIMU can be fully controlled via the digital pins. Another optional pin, the digital data input (DI) can be used for chaining several monitors together.

The DOCIMU consist of 2 separated shielded boxes placed on a PCB, one with the sense part (Sense Unit, Bypass, S/H, Compensation, Over-current, Input Digital Potentiometer and Calibrator) and the other one with the control part (Output Filter, Comparator, 16-bit D/A, 16-bit A/D with the Switch and the Control Unit). The main purpose of the sense part is to measure the I_{DDQ} so that the ATE can read the results or it can configure the monitor via the control part.

The Sense Unit converts the I_{DDQ} current accurately to a corresponding V_{IDDQ} voltage with a ratio 5.00mV per µA. Semidigital monitors are often suffering from electro-magnetic interference (EMI), as the $V_{P/F}$ limit is set externally using an analogue ATE pin. In addition, the analogue outputs of some testers have a poor resolution, which further degrades the performance of a semidigital monitor. The DOCIMU solves both issues, using a precision serial D/A converter, which generates the internal pass/fail voltage level with a resolution of 76µV (15nA). The Output Filter limits the bandwidth, which decreases the noise level. The measured V_{IDDQ} is compared with the $V_{P/F}$ limit by the Comparator, resulting in the pass/fail flag.

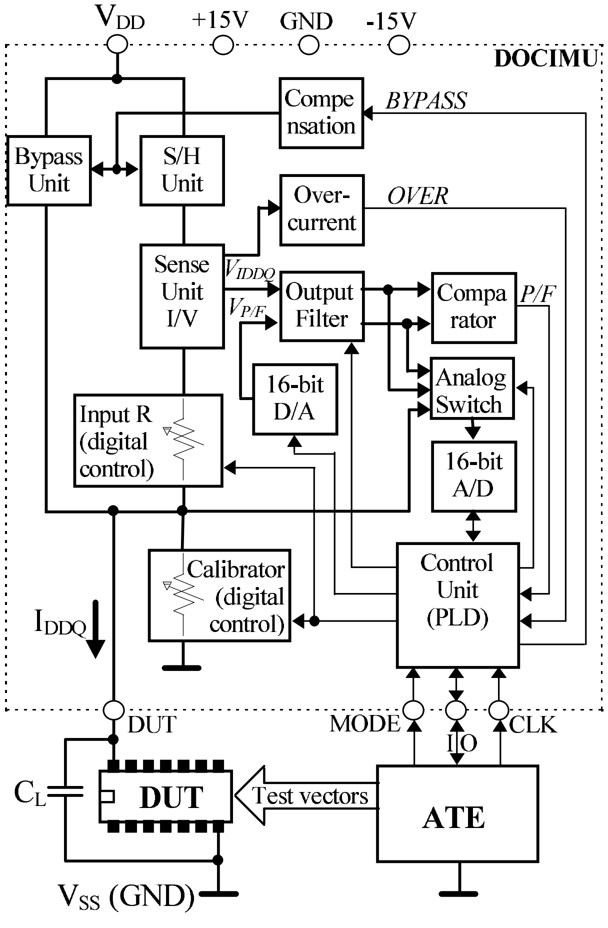

Figure 1. Block schematic of the DOCIMU.

The monitor uses a high speed precision serial 16-bit A/D converter (10µs conversion time), which enables to measure the exact I_{DDQ} value in one measurement cycle. The ATE can also perform a binary search procedure based on using the D/A and the pass/fail flag. This is more accurate, but it takes multiple measurement cycles until exact I_{DDQ} value is found.

All the control logic is implemented in a single component - a high density Programmable Logic Device (PLD). The use of a PLD with in-system programmability provides excellent flexibility as it can be reprogrammed directly on the board, without removing the PLD from the socket. The PLD also saves space, improves and simplifies the PCB and lowers the radiation.

The configuration of the monitor is stored in a 24-bit shift register controlled by the ATE. This register drives analogue switches, which select the monitor's working configuration. 8-bits select the Input Resistance of the DOCIMU and 4-bits determine the cut-off frequency of the Output Filter. As a result, the ATE can optimise the DOCIMU for a wide range of loading capacitance and measurement speeds.

The A/D converter can not only be used to measure the V_{IDDQ} voltage, but also the output voltage of D/A, the $V_{P/F}$ voltage, the actual voltage at the DUT terminal etc. This is a very important feature, as it makes the monitor testable and the ATE can verify, if the monitor works properly. The Analogue Switch at the input of the converter occupies 4 bits from the configuration shift register.

The Calibrator of the DOCIMU offers a set of calibration resistors (up to 8-bits), which serve the ATE to check and to calibrate the offset and the gain error, when an accurate measurement is required.

2.2. The DOCIMU operation.

A new measurement cycle is initated by the ATE by placing the monitor in bypass mode and holding MODE pin 'high' while a new test vector is applied to the DUT, as illustrated in figure 2.

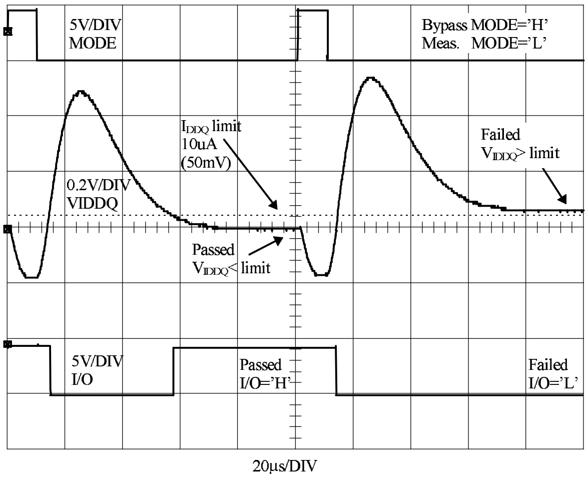

Figure 2. A typical measurement cycle

During this mode the Bypass switch is turned on to bypass the (high) transient current drawn by DUT. The Bypass Unit together with the decoupling capacitor C_L ensures that the operation of the DUT is not affected during this critical period. The MODE pin not only controls the Bypass, but also the direction of the I/O pin. In bypass mode, the I/O pin acts as a serial data input, enabling the ATE to load the 16-bit D/A (I_{DDQ} limit) and the 24-bit configuration shift register.

When the MODE signal is 'low', the monitor is placed in measurement mode, I/O becomes an output and the Bypass switch is turned off. At the end of the measurement cycle, V_{IDDQ} is settles and the ATE can read a valid pass/fail flag via the I/O pin or it can start the A/D conversion. The I/O pin is 'low' (fail), if the measured I_{DDQ} exceeds the I_{DDQ} limit determined by VP/F, otherwise I/O is 'high' (pass).

2.3. New features of the DOCIMU

The Performance of the monitor depends mainly on the Sense Unit. The sense opamp converts the I_{DDQ} to a V_{IDDQ} voltage via a feedback resistor R_S, while the voltage at its inverting input is following V_{DD}, due to the regulating loop, as shown in figure 3.

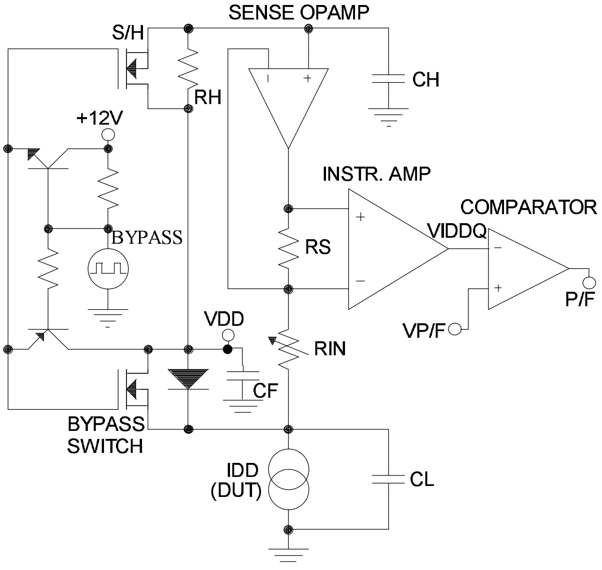

Figure 3. Bypass compensation and S/H feature

The variable input resistor R_{IN} determines the pulse response and limits the noise gain. A too low input resistance results in damped oscillations and excessive output noise, while a too high input resistance makes a voltage drop and slows down the pulse response. A high loading capacitance C_L requires a low R_{IN} and vice versa. R_{IN} is typically 5Ω τo 100Ω for C_L ranging from $2\mu F$ to100nF. The voltage across the sense resistor R_S is further amplified by the instrumentation amplifier. V_{IDDQ} is derived from the I_{DDQ} using a conversion ratio of 5mV/µA, since R_S=1kΩ and the amplification factor is set to 5.

I_{DDQ} monitors usually use a MOSFET switch to bypass the high transient I_{DD}. However every MOSFET has parasitic capacitors Cgs and Cgd, which are important, as they can have a value of a few nF for low R_{ON} MOSFETs. The resulting charge injection when the MOSFET is switched off, causes the peak at the end of the bypass mode (fig. 2). The settling takes time and prolongs the measurement period. On-chip methods [2], to compensate the switch, cannot be applied in designs with discrete components, as single components have a much higher dispersion of parameters than matched on-chip components. However, the DOCIMU is equipped with an auxiliary circuit, which reduces the peaks approximately 5 to 10 times in comparison with an uncompensated bypass switch and therefore the settling is improved about 2 time-constants $R_{IN}C_L$, as illustrated in figure 4. Both compensation bipolar transistors require no matching and they can also be replaced by MOSFETs with low parasitics. The BYPASS control signal is derived from the MODE signal, using an optocoupler.

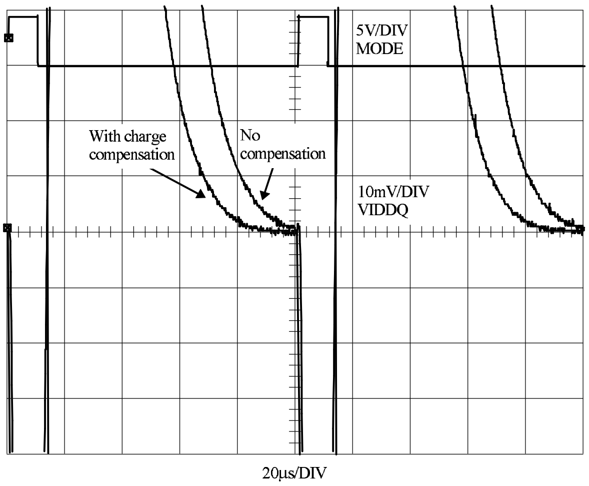

Figure 4. Detail of the settling.

Traditional voltage based testing of digital ICs obviously does not require a high quality V_{DD} supply. However a noisy V_{DD} reference makes a noisy I_{DD}, so I_{DDQ} testing is affected naturally. The V_{DD} power supply provided by the ATE is too noisy for precision I_{DDQ} measurements, as its spectrum exhibits a line ripple (50Hz), switching noise, thermal noise etc. This causes a problem, as the V_{DD} noise cannot be filtered simply without prolonging the V_{DD} reaction time. In engineering / production testing, it can be desired to measure the I_{DDQ} for different V_{DD} voltages. In addition the V_{DD} is set to zero whenever the DUT is removed or placed in the test fixture not to damage the DUT. Therefore, an I_{DDQ} monitor should settle and be ready to measure within a reasonable period (a few ms) after a V_{DD} change occurs. The existing I_{DDQ} monitors either ignore the V_{DD} noise or just place a capacitor between V_{DD} and ground. Since the internal resistance of V_{DD} power supply is very low, this simple RC low-pass does not cut off the AF noise.

The DOCIMU is equipped with a special double sample/hold feature to reject V_{DD} noise & ripple. The used principle is relatively simple, but extremely efficient. Actually there are two S/H circuits in the DOCIMU (fig. 3). Normally the Bypass MOSFET is considered only as a bypass switch, but in reality it is a sample switch and the decoupling capacitor C_L acts as a hold capacitor. If also a S/H is added to the noninverting input of the sense opamp, then the DOCIMU achieves an excellent V_{DD} noise rejection ratio. This unique approach is based on fact that instant value of any AF noise, ripple or interference, which modulates the V_{DD}, is sampled during bypass mode and held in the measurement mode. The essential thing is that there is exactly the same instant value of the V_{DD} voltage at both the opamp's inputs, as the samples are taken at the same time. The matching of both S/H circuits is not critical at all, but both MOSFETs should be capable to charge their hold capacitors in period shorter than 10µs in order to cover whole AF spectrum <10kHz. Elimination of the V_{DD} noise is possible using the S/H feature, as the I_{DDQ} monitor is basically a band pass. Its DC gain is 1 (follower) from V_{DD} point of view, then the gain is growing with frequency due to decreasing impedance of C_L and finally the gain is falling down at high frequencies due to the opamp's gain bandwidth. The double S/H feature enables to separate the V_{DD} noise, which would be normally highly amplified, from the DC based I_{DDQ} measurement.

2.4. DOCIMU specifications

- 2 supply pins, 2 current measurement pins, 3 digital interface pins (CMOS/TTL level)
- Test speeds: from 35µs to 500µs (30kHz to 2kHz)
- Range of the loading capacitance C_L: 100nF - 2µF
- Measurement range: 0 - 1000µA
- I/V conversion ratio: 5.00mV/µA
- Resolution: 50nA - 1µA
- Total accuracy: resolution+0.2% from the value
- Range of DUT's V_{DD} : 1V - 8V
- Monitor's supply voltage: symmetrical +15V/-15V
- Max. transient current I_{DDT} : 10A
- Internal resistance in bypass mode: <0.05Ω
- Internal resistance in measurement mode:
  2.5Ω – 100Ω (according to the configuration)
- Size of the monitor: 22cm x 8cm x 2cm

3. Measurement results and verification

The DOCIMU, as shown in figure 5 is expected to replace its semidigital predecessors (OCIMU and POCIMU), which are successfully used by Alcatel-Bell and Alcatel-Mietec in Belgium for engineering and production I_{DDQ} testing already for several years. In order to evaluate monitor's accuracy exactly, a set of well known resistors was used instead of ICs. The absolute error (i.e. resolution) ΔI_{DDQ} is determined the by peak-to-peak value of the output noise, which is growing with the loading capacitance C_L and the measuring frequency f, as shown in figure 6.

The measurements also confirmed a very high V_{DD} noise rejection. A sine waveform was modulated on supply V_{DD}=5.000V and swept to emulate properly the external noise/ripple/interference. A 10mV magnitude caused a drastic degradation of the resolution, if only traditional RC low-pass filter was used. On the other hand, the new DOCIMU with the double S/H feature, exhibits no or neglectable resolution degradation under the same test conditions. The double S/H improves the resolution approximately 100 times when high level AC signals are modulated on the V_{DD}. The S/H exhibits the high rejection in the whole AF range, while the spectrum above 10kHz is cut-off by the filtering capacitor C_F. Other measurements showed that the DOCIMU reacts very quickly to V_{DD} changes - 100µs is sufficient to sample the new V_{DD} value.

Table 1 shows a comparison of the basic parameters of existing off-chip IDDQ monitors including the DOCIMU.

Figure 5. DOCIMU

I_{DDQ} Monitor [reference]	QuiC-Mon [4,13]	Advantest [16]	Megatest [15]	IDUNA-2 [4]	BIC [21]	IOCIMU	DOCIMU
Developed by	Sandia Labs USA	Advantest Japan	Megatest USA	Philips Holland	UBISTA group Slovak/Belgium	UBISTA group Czech/Belgium	UBISTA/Alcatel Czech/Belgium
Implementation	discrete	discrete	discrete	CMOS 0.8	CMOS 0.7	BiCMOS 2um	discrete
measurement principle	Keating-Meyer	opamp I/V converter	opamp I/V converter	current mirror	CCII+ Current Conveyor	opamp I/V converter	opamp I/V converter
Max. speed f	250kHz	1MHz	50kHz	50kHz	2MHz	20kHz	30kHz
Max. f at CL=100nF	10kHz	10kHz	50kHz		20kHz	20kHz	30kHz
Max. resolution			10nA		500pA	200nA	30nA
resol. at CL=100nF	~ 500nA	~ 1uA	~ 30nA	10uA	3uA	200nA	30nA
Accuracy at 10uA	~ 5%			20%	3%	3%	1%
Output value via	8 bit A/D	A/D	A/D	pass/fail flag	pass/fail flag	pass/fail flag	16bit A/D, pass/fail flag-16 bit D/A
VDD variation	high	1V	0.7V	300mV	~ 200mV	<100mV	<100mV
I/O control pins	~ 3			4	3	3	3
Other interesting features	high speed at low CL	high-speed current source	wide range	small size	small size optimised as on-chip monitor	small size, integrated 0.5Ω bypass	EMI immunity, testability, wide IDDQ range

Table 1. Off-chip IDDQ monitors - review

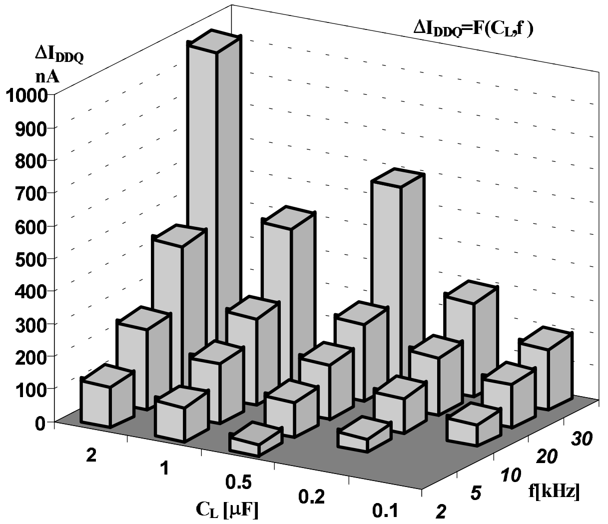

Figure 6. Resolution ΔI_{DDQ}

4. Conclusions

A new Digital Off-Chip I_{DDQ} Measurement Unit is presented. The main advantage of this unit is a relatively high accuracy in wide measurement range at reasonable speed, while the circuit under test is unaffected by the I_{DDQ} testing. The DOCIMU is a testable monitor, it exhibits a high EMI immunity, due to the digital control, the double S/H feature and the special shielding. The unit is versatile, flexible and it provides a cost effective I_{DDQ} measurements and is applicable to a wide range of digital as well as analogue ICs.

In the future the DOCIMU will be probably implemented in silicon via extension of the IOCIMU chip. All existing integrated I_{DDQ} monitors are semidigital. Therefore, it is expected that the integrated DOCIMU will overcome them in versatility and EMI immunity.

Acknowledgements

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