Library Harmonization Project

Energy as an independent library cell characterization dimension

by John Michael Williams

Introduction

Energy is a common quantity. Energy conservation is an important "bottom line" quantity used to verify results of various computations or to measure various effects. Various forms of energy are commensurable:

Kinetic energy in mechanics: $U_k = \frac{1}{2}mv^2$; *m* is mass; *v* is speed. (1)

Potential energy in mechanics: $U_p = kx$; k is a constant; x is a distance. (2)

Heat energy: $U_T = \frac{3}{2}k_BT$; k_B is Boltzmann's constant; *T* is temperature in K.

Energy in an electrical circuit may be defined "kinetically" by the electromagnetic field, for example, by integrating the Poynting vector, $\vec{S} = \vec{E} \times \vec{H}$, which gives power per unit area *A*, so that,

$$U_{EM} = A \int dt \vec{\mathbf{S}}$$
; often, $U_{EM} \cong A \cdot t \cdot \left| \vec{\mathbf{E}} \right| \cdot \left| \vec{\mathbf{H}} \right|$ or $U_{EM} \cong A \cdot t \cdot E^2$, (3)

when \mathbf{E} and \mathbf{H} are perpendicular, as in a plane wave.

We are more interested in forms easily expressed in layout terms: These forms of energy are calculated by kinetic-like formulae, as in Eq. (1), but they represent potential energy:

Energy stored in the electric field of a capacitor:

$$U_C = \frac{1}{2}CV^2$$
; C is capacitance (farads); V is electric potential (volts). (4)

Energy stored in the magnetic field of an inductor:

$$U_L = \frac{1}{2}LI^2$$
; *L* is inductance (henrys); *I* is current (amperes). (5)

The typical capacitance of a storage cell in deep submicron layout is in the femtofarad to picofarad range, somewhere around $50 \cdot 10^{-15}$ F to $1000 \cdot 10^{-15}$ F. Typical inductance of traces in a similar layout is in the range of picohenries per

micron [may be revised]; RF IC designs may use lumped, sometimes micromachined, inductors of 0.1 - 100 nH as filters (chokes) or tuned circuit elements.

Inductance *L* can be estimated from cell geometry and composition, or measured in-circuit. At a given operating temperature, it may be expected to vary very little over time on-chip, because ordinary chip operation has little effect on the magnetic properties of the layout.

Capacitance *C*, on the other hand, depends on charge carrier movement and is sensitive to local electric fields; the capacitance of many layout features, such as P-N junctions, depends on their state.

Notice the relationship between power and energy in Eqs. (4) and (5): Ignoring resistance R, and assuming that capacitance and inductance are constant,

Power =
$$P_C = \frac{dU_C}{dt} = CV\frac{dV}{dt}$$
; and, (6)

Power =
$$P_L = \frac{dU_L}{dt} = LI\frac{dI}{dt}$$
. (7)

Thus, power is consumed or supplied (energy is stored or released) during charge or discharge of a capacitive element ($dV/dt \neq 0$), or during a change in the amount or direction of current flow in an inductive element ($dI/dt \neq 0$).

Power in Eqs. (6) and (7) is reactive power and is not associated as such with mechanical work or dissipation by heat. Power in general has to be expressed as a complex quantity; for example, it may be lumped as $P = V^2/Z$ or $P = I^2Z$, with the impedance Z = R + jX a sum of real (resistive) and imaginary (reactive) components.

A capacitive element can consume power and store energy with little real (resistive) power dissipation; however, leakage of charge will cause loss of energy and eventual dissipation as heat in the substrate or elsewhere. Nevertheless, there is no implied decay of capacitive energy in the capacitive element described by Eq. (6).

An inductive element, though, always does some work by the current *I* against resistance, at least at ordinary temperatures. Thus, it is implied by Eq. (5) or (7) that energy stored in an inductor's magnetic field will be dissipated relatively rapidly as heat at least in part in the inductive element itself.

Gates, traces, and geometric features in general on chip may be attributed either lumped or distributed values of capacitance or inductance. These values may vary with operational state or temperature. The concept of energy is useful to compare these C and L values as well as to convert one into the other in terms of characterization.

Two Energy Characterization Problems

We wish to characterize a cell by energy in order to estimate (*a*) effects of *electrical* energy on normal operation as well as (*b*) effects of *nonelectrical* energy on operation and composition of the cell. Knowing how energy from outside affects a cell implies that we know how energy is used internally by the cell.

We assume that external *electrical* energy will be delivered only on the connections of the cell. *Nonelectrical* energy would include conducted heat, mechanical motion (bending, compressing, stretching, sound, etc.), and particle invasion. Invasive particles might be photons (gamma rays, X-rays, light, radiant heat, microwaves, etc.) or massive particles such as alpha, beta, or neutrons.

It seems that all cell characterization problems should be describable either by cell functionality; or, failing that, by cell geometry and composition. The latter may be called structural for brevity. So, we refer to *functional* or *structural* characterization. In either case, the cell, actually a model of it, should be put in a variety of states, in each of which it will be characterized.

Functional Characterization - Electrical Only

This requires description of a standard way to simulate injection of electrical energy on the pins of a cell, and a way of identifying the effect during transistorlevel netlist evaluation.

Input: Apply a pulse, or a train of them, with characteristics derived from normal operating conditions.

Output: Measure switching thresholds for digital cells, and operating curves in various (amplifier?) configurations for analogue cells.

Structural Characterization - Nonelectrical and Electrical

This requires a description of the geometry and composition of a cell regardless of its overall functionality but attending to elementary substructures such as P-N junctions, FETs, trace lengths, via depths, oxide thicknesses, etc. In general, a transistor netlist model alone is not adequate for this kind of characterization.

Input: Localized application of nonelectrical energy.

Output: Electrical, the same as in Functional Characterization above.



Characterization Generalities

Figure 1. Cell characterization flow according to the Advanced Library Format standard (ALF; IEEE Std 1603).

As shown in Fig. 1, a typical characterization flow for a library cell is as follows: A design specification for the cell is created, and a layout editor is used to implement the design in GDSII physical layout file format. Operating parameters of the implemented cell in a variety of layouts are measured and recorded. Coordinated with these measurements, a layout extraction tool is run on the GDSII to create a transistor-level simulation netlist representing the cell in SPICE or an equivalent netlist file format.

A characterization tool then simulates or otherwise evaluates the netlist model in order to create a characteristic parameter set for the library cell. The parameters are calculated by evaluation over process, temperature, power supply and logic-level voltage, and other variations, so that the cell's performance is obtained independently of the cell specification. If the cell is found not to meet specifications, the design or layout must be changed. The characterization tool also uses the design specification to insert timing checks and other functionality not present in the physical layout.

Parametrization of the netlist model using an intervening set of library-specific variables is the hallmark of characterization.

Energy directly enters into cell characterization in four different ways: (a) Threshold behavior; (b) noise immunity; (c) upset immunity; and, (d) power usage.

Threshold behavior refers to input energy required to change the state of a gate or a sensor. Noise immunity here refers to inability of persistent or frequent energy input, input or internal, to cause a spurious change of state. Effects of temperature or crosstalk fall into this category. Upset immunity refers to inability of rare-event energy inputs, input or internal, to cause a change of state. Ionizing radiation events or power surges fall into this category. Power usage refers to the rate of energy input or output required under normal operation of the cell.

Energy in Liberty® : The Hyperbolic Noise Model

In the Liberty User Guide of 2003-10, volume I, pp. 11-1 - 11-12 and pp. 11-28 ff., energy is invoked directly to define noise immunity. In this guide, which we shall call *Liberty* for brevity, noise is considered to be of two kinds, delay and functional. Delay noise is caused by energy transfer while a cell or trace is changing (during ramp or slew time). Functional noise is caused by energy transfer which causes a (perhaps brief) spurious new logic level to occur.

The hyperbolic noise model is based on a formula for energy which reduces to $U = voltage \times time$, which may be rewritten as V = U/t, because voltage is a

convenient, measurable quantity. The implication is that energy is transferred at a constant rate, so it may be represented as a rectangular pulse of height V and width *t*. We shall not discuss noise in the Fourier transform space here. Thus, the hyperbolic model implies a pulse as in Fig. 2. This graphic was created in MathCAD®.



Figure 2. Noise pulse shape assumed by hyperbolic model.

To account for a voltage threshold, below which no noise effect will be found, a constant A is added, so that the noise energy must cause a voltage change at least equal to A before there is any effect. So, the model then is V = A + U/t. Likewise, a time threshold C is defined below which the noise energy can not cause an effect, making the model, V = A + U/(t - C).

Replacing the above model parameters with meaningful names, *Liberty* p. 11-10 and Fig. 11-4 represent the hyperbolic model as,

$$height = height_coefficient + \frac{area_coefficient}{(width-width_coefficient)}.$$
(8)





An example of this model is plotted in Fig. 3. Notice that the arms of the hyperbola have the two thresholds as asymptotes. The region above and to the right of the hyperbola represents a cell above threshold and thus resistant to any effect of the noise under consideration.

2004-04-28

A noise "glitch" in *Liberty* is viewed as a voltage superposed on some voltage level, high or low, and may be negative or positive. The shape of such a glitch is given as a peaked curve with a long trailing tail. Let us see how this shape occurs:

Suppose originally there was a noise pulse with

rectangular shape, as in Fig. 2 above. To see how this pulse is "sampled" by a capacitive element such as an input gate or trace, we assume an exponentially decaying sampling function, $e(t) = e^{-t}$, and calculate a convolution of it, up to time *t*, with the original pulse. Call the pulse s(t), and assume it is 0.4 time units wide and 1 voltage unit high. Then, the sampled pulse is given by,

$$s_1(t) = s(t) * e(t) = \int_{-\infty}^{t} du \cdot s(u) e(t-u).$$
 (9)

But, suppose the reactive decay is distributed and not lumped. Then, we may approximate this by repeating the sampling--here, just once. We then have,

$$s_2(t) = s_1(t) * e(t) = \int_{-\infty}^t du \cdot s_1(u) e(t-u).$$
(10)



The pulse and the two sampled functions are shown in Fig. 4. The pulse is 0.4 time units wide. Note that the samples are delayed in time relative to the pulse, an effect which would be expected in a real cell or trace.

The shape of $s_2(t)$ is about the same as the glitch shape used to illustrate the *Liberty*

Figure 4. A pulse and the shapes of two sampled device responses to it. Sampling is by exponential decay, as would be the case for a single lumped RC filter. The sampled functions are scaled up in height for better visibility.

discussion of noise immunity. Its area represents the glitch energy.

So, it appears that the Liberty hyperbolic model is designed for a lumped, nondecaying input pulse, but the glitch modelling is for a distributed response. What does this mean in terms of accuracy?

To answer this, let's assume a pulse as above, but 0.2 time units wide, and two different sampling functions, an exponential decay e(t) as above, and for variety a gaussian defined by $g(t) = e^{-(t/sd)^2}$, with sd = 0.1 (a result of some experimentation; the *sd* parameter is not the same as the standard deviation of a normal distribution in statistics). Call the exponentially sampled result, samE(t) = s(t) * e(t), and the gaussian sampled one, samG(t) = s(t) * g(t), with the convolution up to *t* defined as previously.

Looking at the result as compared with the original pulse s(t), we see in Fig. 5 below that the gaussian decay is much faster than the exponential one, as might have been anticipated by the powers in the exponents.



Figure 5. A rectangular pulse and two sampling functions, with sampled results. The sampled results have been scaled up to equal the height of the pulse.

Recalling that area corresponds to energy, these sampled results easily may be compared with the Liberty hyperbolic model in Fig. 3 by replacing the *area_coefficient* term in Eq. (8) above with the sampled function. So, setting all coefficients to 1, we shall compare,

$$V(t) = 1 + \frac{1}{(t-1)}$$
 with $V(t) = 1 + \frac{samE(t)}{(t-1)}$ and $V(t) = 1 + \frac{samG(t)}{(t-1)}$. (11)

v. 0.5

This is done in Fig. 6:



Figure 6. Hyperbolic model V(t) of rectangular noise compared with a model VE(t) with exponential decay and VG(t) with Gaussian decay. All functions as in Fig. 5 and Eq. (11) of the text.

Notice in Fig. 6 that both of the sampled decay functions show a breakpoint at t = 1.1, which represents the end of the applied pulse, which was centered at t = 0, as shown in Fig. 5.

What is important is that both of the decay curves fall below the hyperbolic model curve. This means that, given the normalization of Fig. 5, the *Liberty* hyperbolic model should be conservative, in that it seems to define a higher threshold than would be necessary when considering the distributed impedance causing the shape of a *Liberty* glitch. This makes sense, because a pulse causing a glitch in general will contain more energy, concentrated more in time and space, than the glitch itself.

Energy Functional Characterization

It seems that a SPICE or equivalent simulation netlist should be sufficient for energy functional characterization.

For a digital cell, all input logic states should be enumerated; all internal states should be enumerated, too, if the cell includes storage. For brevity, this combined enumeration will be referred to as the "cell" state set.

For each cell state, the inputs should be

This requires description of a standard way to inject electrical energy on the pins of a cell, and a way of measuring the effect.

The input suggestion here is to apply a pulse with characteristics derived from normal operating conditions. For example, for a digital cell with rise time t_R and fall time t_F , perhaps a pulse of duration $t_R + t_F$ and variable height might be applied. The energy of such a pulse would be proportional to $(t_R + t_F) \cdot V$, with *V* the height in volts.

The output suggestion here is to measure switching thresholds for digital cells, and operating curves in various (amplifier?) configurations for analogue cells.

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Energy Structural Characterization

Jmw Notes

WinSPICE3 References

User Manual, p. 63 - 64: Level 4 & 5 BSIM params (BSIM1 & BSIM2) all are values obtained from process characterization and can be generated automatically.

Univ of Utah IC Design

IC Design UU: Details for characterization = prop delay, rise & fall time, pin cap, setup & hold time.

EE Times Soft-Error Basics

EET_Cataldo_SoftErrs20010818.txt:

A particle with as little as 10 femtocoulombs has enough energy to change the state of an SRAM cell today. Ten years ago it would have taken about five times more energy. "There are lots of particles that are swimming around that can upset a cell," IBM's Lange said. ...

As few as two or three atoms of uranium or thorium contaminating a package are enough to flip a bit. Alpha particles like these usually have a range of only 25 nanometers, Lange said, and can often be shielded by placing a plastic coating over the die.

But cosmic rays are almost impossible to stop. "They'll go through 5 feet of concrete without any trouble," Lange said. "As they pass through they can separate [SRSM] junction current flow for 5 ps [and cause a bit to flip]." ...

Faster speeds could increase soft error rates because memory cells are especially prone to error during read and write cycles. ...

...Mosys Inc., with a one-transistor SRAM that uses a multibank DRAM cell but that touts SRAM speed. "The implication is that the bit lines are very short and that makes it less susceptible to soft error rates," ...

at an altitude of 10,000 feet an SER can be 14 times higher than at sea level because of the greater exposure to cosmic rays.

Aghinolfi on CERN RadHard Thresholds

F_Aghinolfi_RadHard_CERN_200012.pdf: Single-event upset thresholds in MeV/(mg/cm²):

Memory Cell 15 DFF Cell 70 Comb. Gate 70

NASA on Single-Event Error Types

SingleEventDefsNASA_2000.txt:

Linear Energy Transfer (LET) - a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV*cm2/mg of material (Si for MOS devices, etc...).

Threshold LET (LETth) - the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm2. Typically, a particle fluence of 1E5 ions/cm2 is used for SEB and SEGR testing.

2.3 If a device is not immune to SEUs, analysis for SEU rates and effects must take place based on LETth of the candidate devices as follows:

]	Device Threshold			Environment to be Assessed						
LETth	<	10	MeV*cm2/mg	Cosmic	Ray,	Trapped	Proto	ns,	Solar	Flare
LETth	=	10-100	MeV*cm2/mg	Cosmic	Ray					
LETth	>	100	MeV*cm2/mg	No anal	ysis	required	. (= "	SEU	immune	e")

Lib2ALF Notes of 2004-02-23

Notes from 2004-02-23:

perfect immunity

John: energy storage for functional integrity, e.g. refresh requirement for dynamic logic, immunity against noise, e.g. cosmic rays, rate of energy loss by leakage. Fundamental idea is to use energy as a primary variable in cell modeling. Define integrity in terms of signal energy versus noise energy.

Look at energy U as parameter: U \rightarrow 0, no noise immunity; U \rightarrow 00,

Lib2ALF Notes of 2003-12-12

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Notes from 2003-12-12:
Liberty UG Notes:
Noise glitch energy required for
effect:
    LibertyUG, p. 553ff.
    Hyperbolic model, p. 560.
    * poss: use convolution to work out rectangles
         for the glitch function in Fig 11-6,
         p. 561.
         Rectangle area A = w^{*}h;
         hyperbola const. = w*h.
    load increases noise threshold: Poss to
    equate load (I) to energy (I*V \text{ or } C*V^2/2)?
    In E = I*V, I is retarded because of X_L;
    in E = C*V^2/2, V is retarded because of 1/X C.
    ("X_L" here is an equivalent, or virtual,
     quantity).
    Retarded here refers to convolution with
    an exponential.
    Table template for propagated noise:
    width in, height in, capacitance: p. 581.
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_____ Proposal: Define an energy parameter for library elements to represent resistance to soft and hard errors. Storage: Hard Soft Transmission: Hard Soft Both: Hard Soft Energy may be used to determine: Discharge time (capacitive decay) Resistance to interference (capacitive or inductive) Resistance to soft error (capacitive or inductive) _____ ALF D9: p. 200 = pulsewidth p. 206 = Noise & noise_margin p. 208 = power & energy p. 213 = measurement annotation ff _____ IEEE: 1 rad = 100 erg/g= 100*[joule/erg]erg/[kg/g]g = 100*[10^-7]joule/[10^-3]kg = 100*(10^-7)*10^3 joule/kg = 0.01 joule/kg. _____ Energy characterization: Two kinds: 1. Functional: Relevant to noise Convolution assume brief pulse, duration less than shortest switching time impedance match? Or, assume std lead length? Need functionality of the cell: gain in various configs,

state-switching thresholds (digital)
must be measured in a circuit of
some kind
2. Geometrical: Relevant to noise or

particle irradiation.