Futures of microcavity to distribute high-frequency clock over than 10GHz

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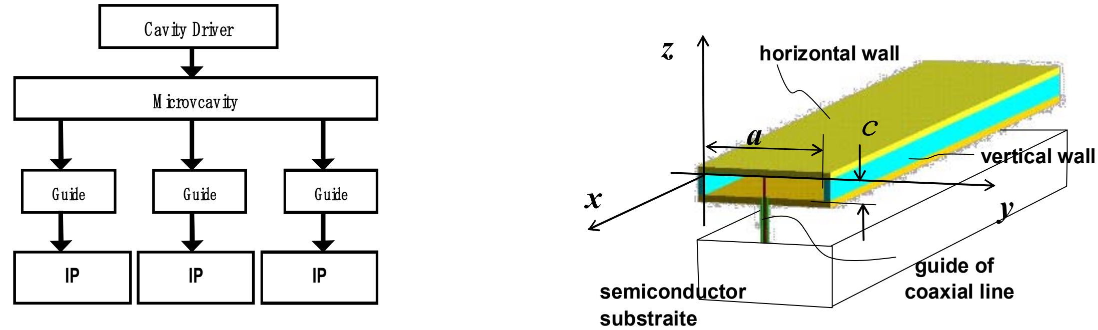
ABSTRACT

We have proposed a novel method of using a microcavity for high frequency clock in ULSI systems. This method can distribute clock signals over than 10GHz without jitter and EMI noise. The microcavity has thin thickness in depth about 5μm and affected by energy dissipation on cavity walls. Considering the effect of energy dissipation, we formulate an electro-magnetic wave using a finite element method (FEM) of vector interpolation function. Applying this method we discuss the features of a microcavity system.

The clock frequency in ULSI systems increases year by year and will exceed 10GHz. At such a high frequency, the signal propagation in a conventional bus line is limited by high-frequency effects such as propagation delay or noise emission [1,2]. Recently, several proposals have been made to improve the high frequency clock distribution including wireless transmission systems [3,4,5] and optoelectronics interconnects [6]. We proposed a novel cavity system to distribute the global clock in a ULSI system. This system uses the standing wave formed in a microcavity as a clock signal and realizes perfectly jitter- and noise-free clock distribution to internal IPs [7].

A block diagram of our system are shown in FIG. 1 (a), which is a system composed of a cavity driver using a planner Gun diode, a microcavity and microwave guides which distribute the signal from the cavity to each IP. A schematic of the cavity structure with a cross section of a microwave guide is shown in Fig.1 (b), which is assumed to be made by a usual metallization process on a semiconductor substrate. A typical dimension of studied microcavity is 5μm in thickness, 3.2mm in width and 12mm in length. In the figure the vertical scale is magnified for convenience' sake to show an inner structure. The top and bottom horizontal walls of the cavity



(a) (b)

Figure 1. A block diagram of a proposed clock distribution system with microcavity (a) and a schematic of a cavity structure fabricated on a semiconductor substrate (b).

can be fabricated by a standard metallization process and the vertical walls is can be made by a via process or can be constructed by an array of via pillars. The thickness of the cavity wall is assumed to be larger than the skin depth, which can be satisfied under clock frequencies over than 10GHz. The proposed system can be implemented into an upper-level interconnect layer of current ULSIs as well as into future 3D-ICs [1,8].

The thickness of a proposed cavity is so thin that resonant mode in a cavity is affected by energy dissipation due to eddy currents on surrounding metallic walls. When energy dissipation is negligible, the resonant mode has vertical electric field and can be analysed as a scalar wave. However, under a strong dissipation an electric field has horizontal components and we must consider it as vector wave. For an analysis of eddy currents φ-A method is widely used, but we employ a magnetic field **H** as unknown variable and use the FEM (finite element method) based on a vector interpolation function. The unknown variables required by φ-A method are at least three. However, a method to use **H** needs only two unknowns because the cavity has thin thickness and a magnetic field **H** is almost in a horizontal xy-plane.

According to a framework of Galerkin method, a functional F of FEM is given by

$$F[\mathbf{W},\mathbf{H}] = \iiint_V \{(\nabla\times\mathbf{W})\cdot(\nabla\times\mathbf{H}) - \omega^2\varepsilon\mu\mathbf{W}\cdot\mathbf{H}\}dV + \iint_S \mathbf{W}\cdot\mathbf{F}_s dS\,. \tag{1}$$

Here, ω is an angular frequency of a forced oscillator, ε and μ are a dielectric constant and a permeability of a filler, **W** is an arbitrary vector field, V is volume region enclosed by cavity walls and S is surface region of V. The vector $\mathbf{F}_s$ is due to eddy currents on cavity walls, which is defined by

$$\mathbf{F}_s = \begin{cases} i\omega\varepsilon(1+i)\mathbf{H}/\sigma\delta & \text{(on metal surface)} \\ 0 & \text{(on open surface)} \end{cases}\ , \tag{2}$$

with σ a conductivity of metal and δ the skin depth defined by $(2/\omega\sigma\mu)^{1/2}$. At each divided element the vector fields **W** and **H** are expanded as follows:

$$\mathbf{W} = \sum_j \varphi_j\,\mathbf{W}_j(x,y)\ , \qquad \mathbf{H} = \sum_j \phi_j\,\mathbf{W}_j(x,y)\ , \tag{3}$$

where φ_j and ϕ_j are edge-element variables and $\mathbf{W}j(x,y)$ (j=1,2,3) are vector interpolation functions without the rotation [9].

The substitution of Eq. (3) into Eq. (1) and variation of F about φ_j yields a simultaneous equation of ϕ_j's. Solving this simultaneous equation by sweep-out method, we can obtain a magnetic field in a cavity for any frequency of forced oscillation. An external current source $I_{ex}e^{i\omega t}$ to excite a cavity can be considered by the boundary condition of ϕ_j such that $\phi_j = I_{ex}e^{i\omega t}$, which is equivalent to give a magnitude of a magnetic field at a divided element.

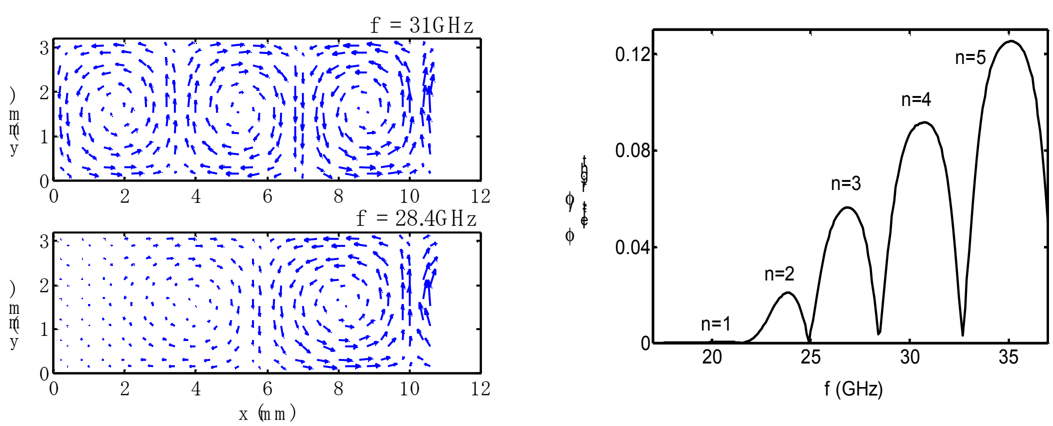
The skin depth δ must be less than the thickness of cavity walls to enclose the microwave energy and to suppress the EMI noise. When the frequency f reaches 30GHz, the skin depth δ becomes about 0.4μm, which is less than a typical wall thickness of 1μm. In Figure 2 (a) field distribution in a cavity is shown by vector map for two different oscillation frequencies: f = 31GHz and 28.4GHz. The cavity dimensions are assumed to be a = 3.2mm in width, b = 12mm in length and c = 5µm in thickness. An excitation source is connected at the midpoint of the left terminal of a cavity, *i.e.* x = 12mm and y = 1.6mm. The vectors in left side near an oscillation source are omitted because those magnitudes are large and the remaining vectors turns to be unclear. When the frequency of a forced oscillator agrees a resonant frequency of the cavity (f = 31GHz), a magnetic field reaches to the end of left side. On the other hand the frequency is out of the resonant condition (f = 28.4GHz), the field strength at the left side turns to be weak.

In Figure 2 (b) a resonance curve is shown, where the horizontal axis is the frequency f of a forced oscillator and the vertical axis is the ratio of field strength at the left and right terminals: ϕ_{left} and ϕ_{righto}. There are five peaks labeled by mode indexes n. If there is no energy dissipation the resonant frequency f is given by

$$f = \frac{1}{2}\sqrt{\frac{1}{\varepsilon\mu}\left(\frac{1}{a^2} + \frac{n^2}{b^2}\right)} \;. \tag{4}$$

Because of the energy dissipation at cavity walls, the peaks in Figure 2 (b) are shifted to the left from the values obtained by Eq. (4). For a peak of n= 1 its frequency turns to be less than the cutoff frequency and the peak is scarcely visible. The q-value defined by the ratio of the resonant frequency and the half-width is about 10 for each peak.

In Figure 3, a dependence of the q-factor, Q, on the cavity thickness, c, is shown for two different materials, namely Cu with BM (barrier metal) and Al with tungsten via. The cavity width is assumed to be 3.2mm and the length is to be 12mm. At the thickness c = 5µm the q-factor Q = 12 and an applicable resonant state is realized. To suppress the clock jitter strictly a high Q over than a hundred is desired, but the thickness c must be 70µm, which is hard to fabricate by a usual metallization process. A possible method to realize this thickness is an upper-level interconnect layer of a future 3D-ICs [1,8].



(a) (b)

Figure 2. The vector map of magnetic fields (a) and a resonance curve (b) of a cavity obtained by the FEM with consideration of a energy dissipation on metallic walls. The cavity dimensions are a = 3.2mm in width, b = 12mm in length and c = 5µm in thickness. A driving current of a frequency f is connected at the right terminal of a cavity.

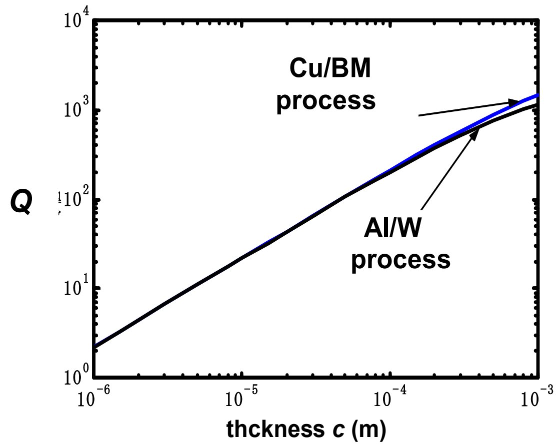


Figure 3. The dependence of the q-factor Q on the thickness c for Cu/BM and Al/W processes. The width a=3.2mm, the length b =12mm and the index of resonant mode n=3.

For a cavity made by a Cu process, the effect of high-resistivity BM is of concern; however, there is seen no substantial effect because the BM is very thin. When the upper and bottom plates are made of Al and the sidewall is by W vias, this process is well founded and economical but its resistivity is larger than that of Cu/BM and results in degradation of q-values. However, its effect is not serious for the cavities thinner than 0.3mm because the area ratio of W against Al is small.

The clock signal is picked up through the microwave guides connected at the places where the amplitude of the standing wave is intensive and equivalent, for example, at the amplitude maximum points or at the points $\lambda/4$ away from the maximum points. Therefore, the number of microwave guides depends on the standing wave number, n, or the harmonic index. The dimension of a microwave guide must be of the order of micron meters because a terminal of the guide is connected to a MOS transistor on a semiconductor substrate. To analyse transfer characteristics of such a fine guide line under the influence of energy dissipation, we also use FEM based on a vector interpolation function and obtained the field distribution as shown in Figure 4.

The microwave guide is assumed to be located at the center of a magnetic eddy in figure 2 (a). The guide line is a cylindrical tube with a core lead, whose cross section is depicted in zr-plane of cylindrical coordinates. One terminal of the guide line is connected to the body of a microcavity and an input field is applied at the fringe labeled by V_{in}., where the magnetic field is normalized to the unity. The oscillation frequency is 31GHz. The inner lead has a radius of R_0 = 0.5μm, the inner radius of the tube is R_1 = 1.5μm and the length of the guide is h = 10μm. The output signal is the voltage between terminals of the capacitive load C_L=30fF connected to the other end of the microwave guide.

Because of the cylindrical symmetry, magnetic field has an angular component H_θ only. The field penetrates up to the end of the guide because an impedance of the cavity and the guide line matches relatively well. The gain defined by V_{out}/V_{in} is 0.3 in magnitude and 1.8^o in phase angle. If the impedance between the external load C_L and the guide line is adjusted, the gain will be improved.

In this paper we discussed a microcavity to distribute a high-frequency clock over than 10GHz. Assuming that a microcavity is fabricated by a usual metallization process and its thickness is

5μm, we analyzed the forced oscillation under the influence of the energy dissipation. In spite of the energy dissipation on cavity walls, a resonant mode spread in every corner of the cavity and the microwave guide can transfer ifs signal. Though these analyses based on a FEM, our proposed microcavity system is confirmed as a promising system.

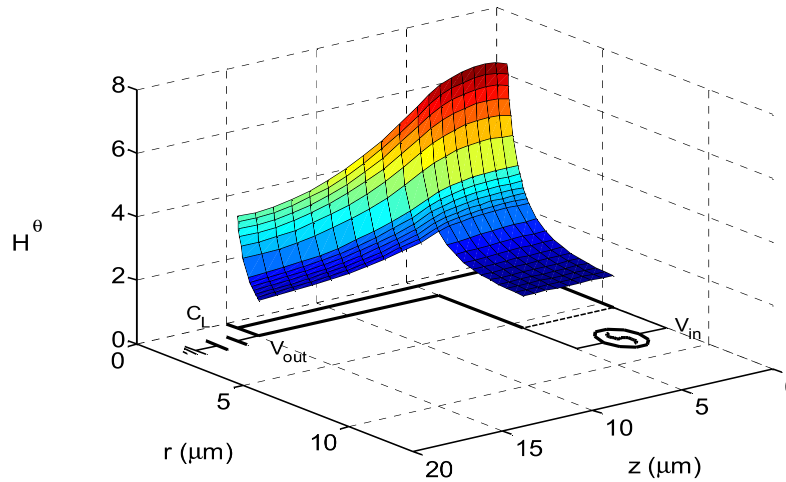


Figure 4. A magnetic field in a microwave guide driven by a cylindrically symmetric input. The guide is a cylindrical tube with a core lead, whose cross section is depicted in *zr*-plane. One terminal of the guide line is connected to the body of a microcavity, and the other terminal has a capacitive load C_L. A magnetic field has only angular component H_θ, whose value is normalized to the unity at the fringe of the input terminal.

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