Hybrid TTSV Structure for Heat Mitigation and Energy Harvesting in 3D IC

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Abstract

Three Dimensional Integration seems to be one of the best candidates to overcome the various challenges and limitations faced by conventional planer integration. But, thermal issues related to this highly promising integration technique are the main bottleneck for wide scale application. This thermal issue threatens the further progress and development of the 3D IC. The best known possible way to reduce the heat generated within the integrated chip is cooling through the thermal through silicon via (TTSV). This work reports the utilization of time dependent fluctuation of temperature which is generated within the active layers of 3D IC. Pyroelectric effect of TTSV materials is used to convert the heat generated within 3D IC to electrical energy. 60K temperature fluctuation within the IC layer was used to convert as electrical energy and 9.89µW output power was observed. This paper reports the novelty of TTSV structure modification where TTSVs are used as simultaneous energy harvester and heat mitigator.

Introduction

The demand for higher functionalities within a single chip is rapidly increasing. To satisfy this ever growing demand and to be on the track of Moore's law device dimensional scaling was performed in such a way that such scaling down has almost reached its fundamental limits. Besides planer integration is facing other challenges as well. The concept of 3 Dimensional Integration can be regarded as a paradigm shift where several device layers with various functionalities are stacked vertically and connected by shorter interconnects than planer interconnects[1]. 3D IC offers other advantages like (1) higher form factor (2) heterogeneous integration (3) improved I/O density and so on [2]. The main challenge for wide scale application of 3D Integration however is the thermal management issues associated with the stacked vertical layers [3]. Introduction of heat path in between hotspots and bottom heat sink is one of the most sought after methods for heat mitigation and reduce the peak temperature generated within the active layers.

With this goal thermal through silicon via are inserted in between active device layers [4]. Several researches have been conducted with the primary objective of heat mitigation and efficient improvement of TTSV [5]. Lee et al. reported the allocation of thermal via for temperature hotspot mitigation for each die in the routing process [5]. With the aim of solving the problem of localized hotspots Hwang et al. proposed the Fin structure and thermal aware TTSV design [6]. Researches have been performed to harvest energy from 3D IC by using thermoelectric effect [7]. For this purpose fabrication of thermocouples along with 3d IC s consumes precious space within the chip without contributing any heat mitigation.

It can further be observed that in a 3D chip with n-layers within it, when the temperature of jth active rises that can be expressed as [8]

$$\Delta T_j = \sum_{i=1}^{j}\left[R_i\left(\sum_{k=i}^{k=n}\frac{P_k}{A}\right)\right]$$

Here n= total number of active layers

Ri = thermal resistance between the ith and (i-1) th layers

P_k= power dissipation in kth layer neglecting interconnect joule heating

It can be observed that at a particular layer the temperature depends on that layer's power dissipation. It can also be observed that this power dissipation depends on that layer's logic usage, which is a time dependent factor. So, non-linear time dependent temperature fluctuations are expected from an IC layer. It is mandatory to have large temperature difference in between two ends of the thermoelectric material to generate reasonable amount of voltage through thermoelectric effect, which is not viable within 3D IC.

On the other hand pyroelectric effect depends on temperature fluctuation to produce electrical energy from heat. Hence, time dependent temperature fluctuations are sufficient to produce electrical energy from active device layer's heat using pyroelectric materials. Y. Yang et al. explained other advantages of using pyroelectric effect over the concept of thermoelectric effect [9].

Herein we propose a novel method of modification of TTSV structure and usage of pyroelectric material which can harvest energy and mitigate heat at the same time.

Modeling & discussion of results

Commercially available FEM COMSOL version 4.2a has been used for simulation. Joule heating module has been used as the physics for the simulation.

TTSVs can be filled with Copper. Copper is an excellent material through which heat generated within the active layers can be channeled to the heat sink. So to investigate the importance of full filling vs partial fill of TSV via we simulated different Cu filled and observed the change in the variation of temperature at different IC levels.

Figure 1 suggests that Beyond ~ 3 µm thick of Cu, TTSV demonstrates cooling capability that closely matches that of TTSV completely filled with Cu. To be very precise it is found to be about 86% heat get removed by only 30% of Cu filling.

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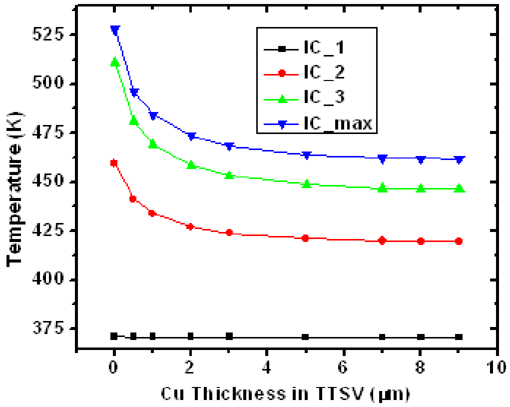

Figure1: Temperature profile at different IC levels for different thickness of Cu and air combination.

Only less than 14% of the total heat can be reduced by the remaining Copper, which is more than 70% of the total Copper content. If this amount of Copper can be replaced from the central TTSV structure by some pyroelectric material, it can be advantageous in two ways. (1) heat can be mitigated (2) reasonable amount of electrical energy can be extracted from the unwanted temperature [10]. From the nonlinear temperature fluctuation, electrical charge is produced within the pyroelectric material [11]. The current generated within the pyroelectric material can be expressed as

$$i_p(t) = pA\frac{dT(t)}{dt}$$

Here p= pyroelectric coefficient of the material in the TTSV center with cross sectional area A

T(t) represents the variation of current with respect to time t.

Figure 2 depicts that in the TTSV structure as an outer cylinder 30% Copper was retained while remaining area was filled with pyroelectric material.

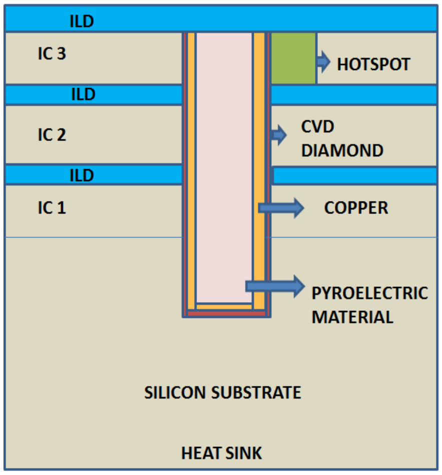

Figure 2: Schematic diagram of simulated model. Cu cylinder with 3um thickness is used as outer layer of TTSV with 20um diameter. TTSV is filled with pyroelectric material with radius 6 um. 1 um thick CVD Diamond used as liner.

In this study three different pyroelectric materials were used for the relative comparison of the pyroelectric current generated within them. These materials are (1) Zinc Oxide (ZnO) (2) Aluminium Nitride (AlN) (3) Barium Titanate ($BaTiO_3$). Table 1 lists all the material properties used in this present study.

To simulate the above mentioned simulation model, uniform heat flux has been assumed through the entire chip. On top of Si layers power density was applied. Interlayer dielectric layers were assumed to have heat flux. Heat generated due to device & interconnects, uniformly distributed across the entire chip. Power density of all devices layer and interconnect were assumed 70W/cm^2 along with bottom substrate at a temperature of 358.3K (heat sink).

Table 1: Material properties of all the materials used for simulation

Material	Thermal conductivity (W/m.K)	Heat capacity (J/kg.K)	Densiy (kg/m^3)	Pyroelectric coefficient (µC/m^2.K)
$BaTiO_3$	2.65	434	6020	200
ZnO	25.2	494.71	5600	9.4
AlN	140	740	3260	4.8
CVD Diamond	1800	502	3515	-
Copper	400	385	8700	-
Silicon	130	700	2329	-

Uniform temperature generated by constant flux within the active layers is not suitable to produce charge in the pyroelectric material. However there is numerous literatures suggested that a lot of hot spot get generated at any point of time at different location. Hence, hotspot with 10 µm^2 area has been considered. Such hotspot is shown in Fig. 2 on IC 3 and 1 µm away from central TTSV. Figure 3 represents the variation of hotspot temperature with time. Gaussian function was used to model this temperature variation having mean 0.5 and variance 0.5. The minimum and maximum temperature for the temperature variation was 465K and 525K respectively.

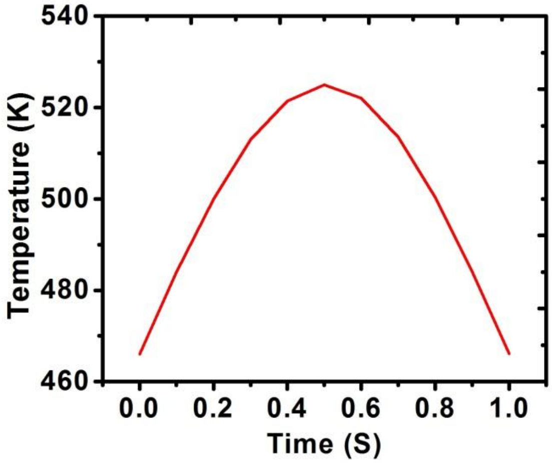

Figure 3: Variation of hotspot temperature with time. Gaussian function is used to model the hotspot with mean=0.5 and variance= 0.5.

To understand the temperature gradient generated within the pyroelectric material, time dependent heat transfer model was utilized.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla . q = Q$$

Where $q = -k\nabla T$, Cp=Specific heat capacity [J/(kg*K))], ρ=Density [kg/m^3], k=Thermal conductivity [W/(m*K)],q=Heat flux [W/m^2], Q= Joule heating =J.E [W/m^3]

Figure 4 shows the relative variation of the current /unit area produced within IC 1 as the hotspot with area 10μm^2 moves away from TTSV. As the distance of hotspot from TTSV increases the temperature fluctuation cannot couple with TTSV, resulting sharp decrement in current.

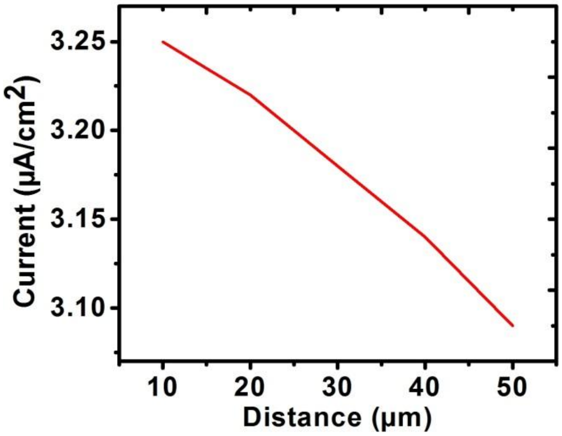

Figure 4: Variation of current generated per unit area as hotspot moves away from TTSV.

Figure 5 represents the relative variation of hotspot variance. Figure 6 shows the variation of current as the variance of hotspot was varied. It suggests that as the temperature curve's slope decreases, which results decrement of current. Figure 7 represents the variation of maximum hotspot temperature while the time period was kept constant. For each maximum temperature corresponding current was calculated and plotted in Fig. 8. Table 2 lists the current generated per unit area for both AlN and ZnO as the distance increases away from TTSV. It is evident that due to higher pyroelectric coefficient of ZnO the pyroelectric current is more than AlN.

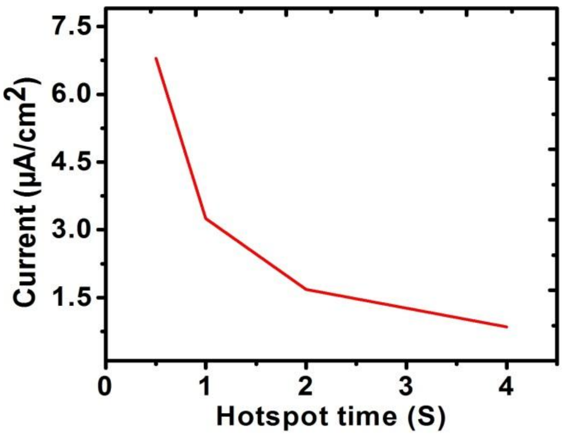

Figure 6: Variation of current with different hotspot variance

Table 2: Relative comparison of current/unit area for ZnO and AlN with increasing distance from TTSV

Distance from TTSV (um)	Current/unit area (μA/cm^2)	
	ZnO	AlN
10	0.153	0.0784
20	0.152	0.0777
30	0.150	0.077
40	0.148	0.0763
50	0.145	0.075

If the hot spot cycle in Fig.3 is periodic then the average output power is calculated and is equal to 9.89μW for the load of 1MΩ. It can be observed that the average output power increases with decrease in variance of hotspot.

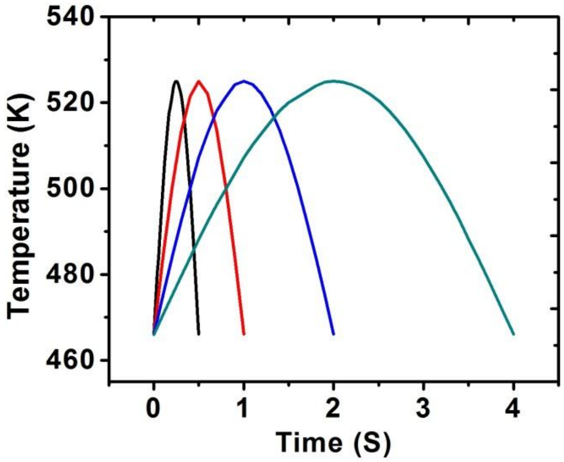

Figure 5: Variation of hotspot variance with different Gaussian means (0.25, 0.5, 1, 2). Slope of each curve decreases with the increment of mean value.

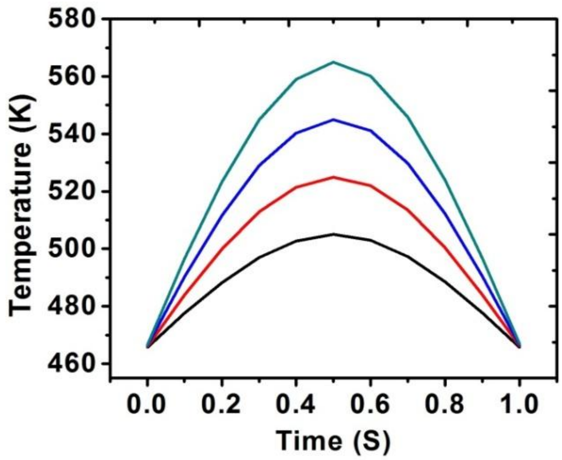

Figure 7: Variation of maximum hotspot temperature with same similar time swing