Contents

Ac	Acknowledgments				
1	Hea	t in int	tegrated circuits and systems	1	
	1.1		ology trends driving thermal issues	2	
			Design closure concerns	2	
		1.1.2	Reliability concerns	4	
		1.1.3	Performance concerns	7	
		1.1.4	Cost- and user-driven, economic concerns	8	
	1.2			9	
		1.2.1	Examples of thermal responses in		
			high-performance chips	11	
		1.2.2	Heat dissipation paths	17	
	Refe	erences		25	
2	On-chip temperature sensing				
	2.1				
			ip temperature sensors	32	
	2.2			37	
		2.2.1	Thermal diode-based sensors	37	
		2.2.2	Resistive sensors	39	
		2.2.3	Thermocouples and thermopiles	39	
		2.2.4	Other types of analog sensors	44	
	2.3	•••		45	
		2.3.1	MOSFET-based voltage/current output sensors	45	
		2.3.2	Time-to-temperature (delay-line) sensors	46	
		2.3.3	Leakage-based temperature sensors	47	
	2.4		r front-end	48	
		2.4.1	Sigma-Delta ADCs for temperature sensors	49	
			SAR ADCs for temperature sensors	50	
		2.4.3	PTDCs for temperature sensors	51	
	2.5	Desig	n challenges for sensors	51	
		2.5.1	Ideality and linearity	51	
		2.5.2	Robustness against variations	53	
			Calibration	56	
	2.6	Impro	wing temperature monitoring accuracy with		
		system	natic placement	59	

3

4

	2.6.1	Enhancing uniform grids with interpolation	61		
	2.6.2	Non-uniform sensor allocation and placement	67		
	2.6.3	Sensor allocation and placement for reconfigurable fabrics	73		
	2.6.4	Recent developments in sensor allocation and placement	78		
2.7	Indire	ct temperature sensing	79		
Refe	erences		80		
Dyn	amic tl	hermal management	89		
3.1	Interfa	acing temperature sensors and DTM systems	90		
	3.1.1	Biasing networks for temperature sensors	90		
	3.1.2	Communication networks for temperature sensor outputs	97		
3.2					
	tempe	rature sensor feedback in industrial designs	100		
		Early methods for DTM	101		
	3.2.2	Second-generation methods for DTM	103		
		Latest generation methods for DTM	106		
3.3		ods on the use of on-chip temperature sensor feedback			
	for dy	namic optimizations beyond commercial designs	109		
	3.3.1	Hardware-based thermal management	109		
3.4	0 0 0				
	feedba	ack from on-chip temperature sensors	121		
	3.4.1	Using sensor feedback for DRAM refresh and write			
		timing optimization	121		
	3.4.2	Using sensor feedback in architectural optimizations			
		for DRAMs	123		
	3.4.3	Using sensor feedback for thermal management in			
		hard drives	124		
3.5		ser look at the control systems for thermal management	124		
		Closed loop (feedback) controller	125		
	3.5.2	Stochastic control	129		
	3.5.3	Model predictive control	131		
Refe	erences		132		
Act	ive cool	ing	139		
4.1	Air co	ooling	140		
		Managing cooling fans	145		
		Beyond fan-based forced air cooling systems	148		
4.2	Liquic	l cooling	150		
	4.2.1	Optimization of efficiency and cost of liquid			
		cooling systems	153		
		Liquid cooling in 3D ICs	156		
	4.2.3	Direct liquid cooling	162		
4.3	Therm	noelectric cooling	163		

		4.3.1 Principles of operation and performance metrics for TEC				
		devices	164			
		4.3.2 Design of latest generation on-chip coolers	166			
		4.3.3 A theoretical analysis framework for thermoelectric coolers	169			
		4.3.4 Using TEC devices for thermal management of ICs	172			
	4.4	Phase change cooling	178			
	Refe	rences	180			
5	Mitigating thermal events at the system level and above					
	5.1	Mitigating heat dissipation at the OS level	191			
		5.1.1 Thermal-aware optimizations	193			
	5.2	OS-level thermal policies for embedded and real-time systems	207			
	5.3	Thermal-aware virtualization	214			
	5.4	The role of the application layer in shaping thermal profiles	219			
	5.5	Thermal-aware optimizations in datacenters and supercomputers	222			
		5.5.1 Characterization of heat dissipation in data centers and				
		performance metrics	222			
		5.5.2 Software environments and provisioning at the				
		system-level for thermal-aware management	226			
	Refe	rences	228			
6	Emerging directions in thermal-aware systems					
	6.1	Considering user comfort in thermal design	233			
	6.2	Thermal harvesting from within integrated circuits	236			
	6.3	New materials and designs for on-chip temperature sensors	238			
	6.4	Hardware security	239			
	Refe	rences	240			
Ar	nend	ix A: Relevant units and metrics	243			
-	Index					