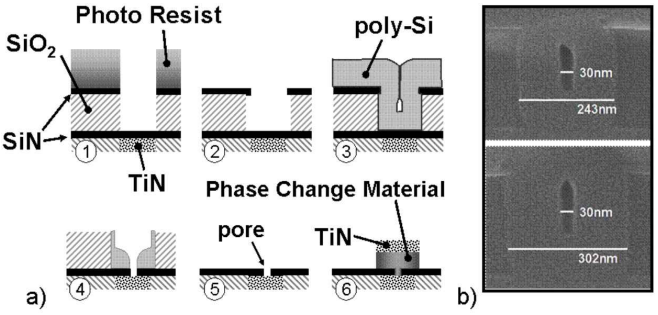

FIG. 20: (a) A sub-lithographic and lithography-independent feature is fabricated using the keyhole-transfer process: 1) A lithographically-defined hole is etched, and 2) the middle SiO_2 layer is recessed. 3) A highly conformal poly-Si film is deposited, producing a sub-lithographic keyhole whose diameter is equal to the recess of the SiO_2 layer. 4) The keyhole is transferred into the underlying SiN layer to define a pore, followed by 5) removal of the SiO_2 and poly-Si. 6) The phase change and top electrode (TiN) materials are then deposited and the cell is patterned for isolation. (b) An SEM cross-section corresponding to step 3), showing keyholes for two different sized lithographically-defined holes. Since the keyhole size does not depend on lithography, the phase change CD can be successfully decoupled from any lithographic variability. Reprinted with permission from Reference [154] (© Springer 2009).

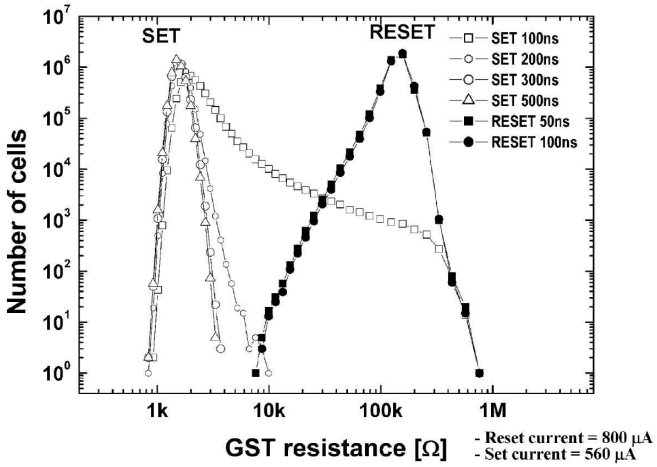

FIG. 21: SET resistance and RESET resistance distributions as a function of the programming pulse width. In this example, while 100ns is sufficient to SET most of the cells to below 2 kΩ, many cells still have a resistance greater than 10kΩ. However, extending the 50ns RESET pulse to 100ns has no noticeable effect on increasing the resistance of the RESET tail. GST refers to the phase change material used in this experiment, $Ge_2Sb_2Te_5$. Reprinted with permission from Reference [164] (© 2007 IEEE).

narrower for pore cells fabricated through the keyhole-transfer method than for those fabricated with a collar process. Similar results have been demonstrated for mushroom cells[122]. Here, mushroom cells with heaters defined with the keyhole-transfer process were compared to otherwise identical mushroom cells with heaters defined by trimming of photoresist islands. This comparison was performed by examining the dynamic resistance R_{dyn} during programming, which tends to exhibit a dependence on programming current I as

$$R_{dyn} = \frac{A}{I} + B. \quad (7)$$

Here the term A depends only on material characteristics, while B incorporates both material and structure-dependent factors[122]. Thus the lower variability in B empirically observed for mushroom cells with heaters defined by the keyhole–transfer method (as compared to those defined by trimmed-photoresist) is indicative of the tighter CD control offered by the keyhole–transfer method.

3. *Impact of structural variability*

Structural variability gives rise to variability in electrical response, which leads to broader resistance distributions after single-shot programming. Figure 21 shows a series of SET resistance distributions, including one (for 100ns SET pulses) which is strikingly broad. Although the majority of cells can reach a low resistance of approximately 2kΩ with a SET pulse of 100ns duration, for this collection of cells there is a subset of devices whose resistances after such a single SET pulse extend all the way out to the fully RESET resistance of several hundred kΩ. For a given programming current amplitude, devices with different diameters will present different dynamic resistances during programming, thus dissipating different amounts of power despite the same drive voltages. This variable power will lead to a different maximum temperature, and even a different temperature distribution within the cell because variations in aperture or heater size affect the thermal resistances within the cell. For RESET pulses, the size of the amorphous plug required to significantly affect the room-temperature low-field resistance of the cell changes drastically with changes in the cross-sectional aperture of the cell. In terms of SET pulses shown in Figure 21, rapid SET requires that the optimal temperatures for crystal growth be present at the crystalline–amorphous boundary (growth-dominated material) or within the cell interior (nucleation-dominated material). Since the crystallization speed is a strong function of temperature (Figure 8), variability in aperture size can result in a variety of incompletely-SET cells if the pulse is too short. As Figure 21 shows, increasing the duration of SET pulses tends to overcome this effect. Another, even more effective route is to ramp down the SET pulse slowly, allowing each cell to pass through the temperature for maximum crystal growth[163].

In addition to broadened resistance distributions, device variability also affects how these resistances evolve over time. It is well known that the resistance of cells in the RESET state tends to increase slowly over time, an effect which has been attributed to either mechanical relaxation forced by the reduced density associated with the amorphous state[165, 166], to the formation of electronic traps associated with lone-pair states which increases resistance by repositioning the Fermi level[91], the annihilation of defects by trap-filling which reduces transport and thus increases resistance[89, 167], or to some combination of these effects. Since this drift in-