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Review Article

Mechanical Researches on Young's Modulus of SCS Nanostructures

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Nanostructures of SingleCrystalSilicon (SCS) with superior electrical, mechanical, thermal, and optical properties are emerging in the development of novel nanodevices. Mechanical properties especially Young's modulus are essential in developing and utilizing such nanodevices. In this paper, experimental researches including bending tests, resonance tests, and tensile tests on Young' s modulus of nanoscaled SCS are reviewed, and their results are compared. It was found that the values of E measured by different testing methods cannot match to each other. As the differences cannot be explained as experimental errors, it should be understood by taking surface effect into account. With a simplified model, we qualitatively explained the difference in E value measured by tensile test and by resonance test for Si nanobeams.

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1. Introduction

Being the most important semiconductor used in microelectronics and microelectromechanical systems, Single Crystalline Silicon (SCS) is still a research hot spot in nanoscience and nanotechnology, as current trend pushes sciences and technologies to nanometer scale. Researchers have found that Si structures would exhibit unique electrical [1], mechanical [2], thermal [3], and optical [4] properties at nanoscale. This makes Si nanostructures (nanobeams and nanowires) attractive in developing Field-effect transistors (FETs), field-emission devices, chemical sensors, nanoresonators, and photonics, and so forth. However, in order to make these devices reliable, mechanical properties, especially Young's modulus (E) of Si nanostructures are essential and critical to study.

Being defined as the ratio of tensile stress to tensile strain, E is always considered as an intrinsic material property and fundamentally related to internal atomic bonding. The stronger the atomic bonding is, the larger the Young's modulus is. Besides the direct testing method, tensile test, there are many other techniques for obtaining E, for example, bending/curvature, resonance, indentation, and so forth. But in nanoscale, it is in question that whether these testing methods are still effective, and where surface effect cannot be ignored.

In this review, we present the recent experimental researches on Young's modulus of SCS nanostructures and compare their E results. It was found that different testing methods showed different values of E. With a simplified model taking surface effect into account, we qualitatively explained the difference that for Si nanobeams E_t measured by tensile test are not the same as E_r measured by resonance test, it may realize that the measurement of E in nanoscale is more complex than in macroscale.

2. Current Experimental Tests on SCS Nanostructures

Mechanical property measurements of nanostructures, such as nanobeams and nanowires, are very challenging because of the difficulties in (1) sample preparation and nanomanipulating and (2) measuring force and displacement (strain and stress) with nanoscale resolution. But in these years researchers have demonstrated some mechanical tests on SCS nanobeams and nanowires, which cover bending tests, resonance tests, and tensile tests.

2.1. Bending Tests. Atomic force microscopy (AFM) is usually employed to give 3D image of the topography of the sample surface, control and apply a specified amount of force on the sample. It is suitable to use AFM in mechanical tests on a single- (double-) clamped nanobeam (nanowire) by applying force to the specimen and measure deformation simultaneously. By using beam bending equations, the mechanical properties can be deduced. For double-clamped beam being applied as a force in its middle point, Young's modulus can be expressed as

$$E = \frac{l^3}{192I} m, \qquad (1)$$

where l is the beam/wire length, I is the moment of inertia for the beam cross-section, and m is the gradient of the force-displacement curve during bending [5].

Namazu et al. patterned Si nanobeams by means of field-enhanced anodization on SOI wafer using AFM and obtained the nanobeams by anisotropic wet etching, which are <110>-oriented with thickness of 255 nm and widths from 200 to 800 nm. By applying bending tests on these double clamped nanobeams, the measured values of Young's modulus are determined to be 169 GPa on average. These results indicate that the specimen size has no influence on E yet [5]. Sundararajan et al. also followed the experimental procedure and presented Young's modulus values of 182 ± 11 GPa [6, 7].

Virwani et al. patterned some 200–400 nm-wide 193/255 nm-thick Si nanobeam on SOI wafer using e-beam lithography, and their bending tests by AFM gave an Si Young's modulus of 174 GPa along <100> direction [8].

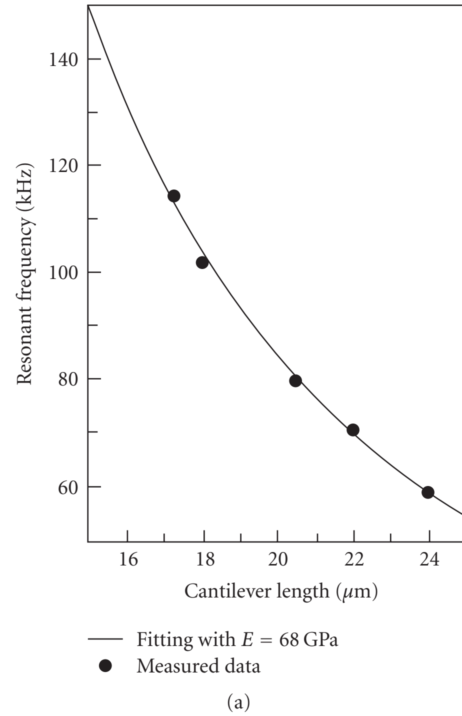
Paulo et al. also used AFM to characterize the mechanical elasticity of their Si nanowires synthesized by Vapor-Liquid-Solid method. The nanowires are horizontally grown between the two facing Si sidewalls of microtrenches. The values of E were estimated to be 186 GPa and 207 GPa, respectively, for single- and double-clamped Si nanowires [9].

2.2. Resonance Tests. According to Euler-Bernoulli theory, dynamic studies on the resonant frequency of nanobeams and nanowires can provide Young's modulus when the geometry is determined accurately.

In the work of Li et al. [10] , the SCS untratine cantilevers were patterned on SOI wafer and dry etched along <110> crystalline direction with thicknesses ranging from 12–300 nm. Resonant properties of the cantilevers were characterized in high vacuum chamber by laser vibrometer. A pulsed light beam from a laser diode excites the cantilever to resonate and another fiber-coupled laser to pick up the vibration signal quality factor Q. The fundamental resonant frequency f_0 was obtained and Young's modulus was deduced using following equation:

$$f_0 \approx 0.162 \left(\frac{E}{\rho}\right)^{1/2} \frac{\mathrm{t}}{l^2}, \qquad (2)$$

where ρ is the material density, t is the thickness of the cantilever, and l is the length. The E was fitted to be 68 GPa for 38.5-nm-thick cantilever, and 53 GPa for 12-nm-thick cantilever, as shown in Figure 1, it demonstrated that Young's



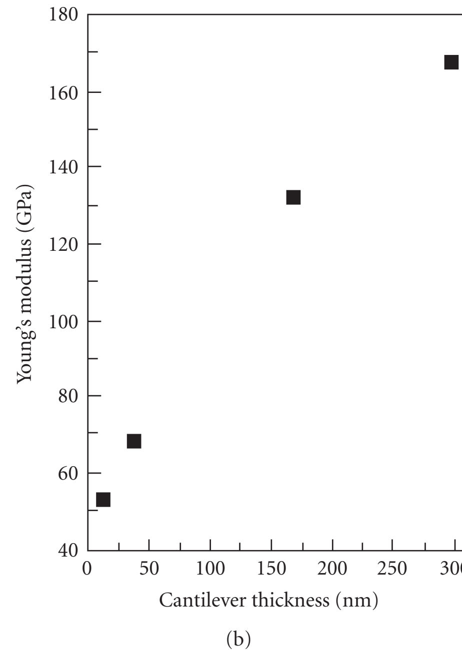


Figure 1: (a) Resonant frequency data for a set of 38.5 nm-thick cantilevers (with varied length) are fitted into theoretical curve based on resonant frequency expression. Young's modulus of 68 GPa is obtained from the fitted result. (b) The monotonous decrease in Young's modulus value of the ultrathin SCS cantilevers is obtained. The thickness of the cantilevers is in the range of 300–12 nm. (Reprinted with permission from [10]. 2003 American Institute of Physics).

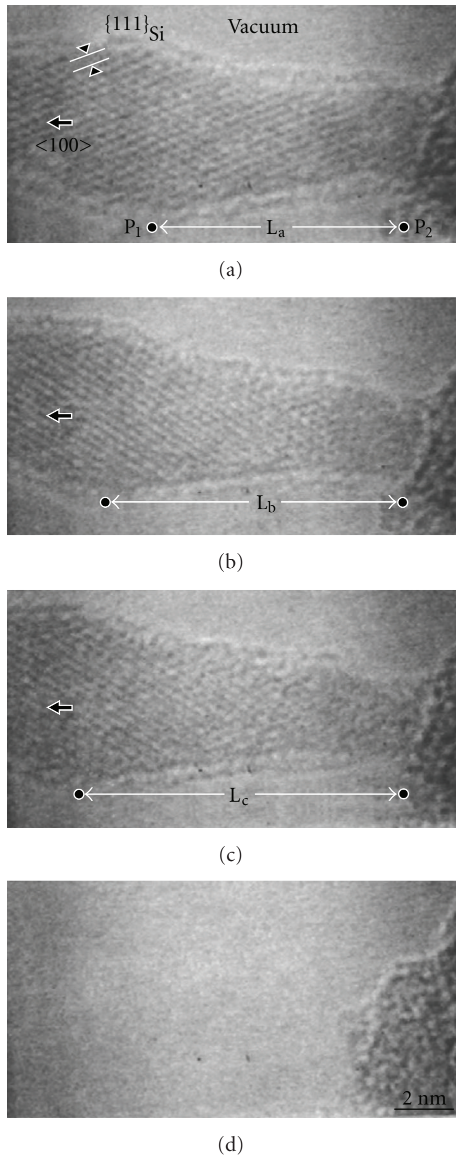


Figure 2: Time-sequent series of high-resolution images of a tensile deformation process of a single crystalline Si nanowire. The tip of the cantilever (the left-hand side) is retracted toward the left as indicated by the bold arrows. (Reprinted with permission from [11]. 2005 American physical Society).

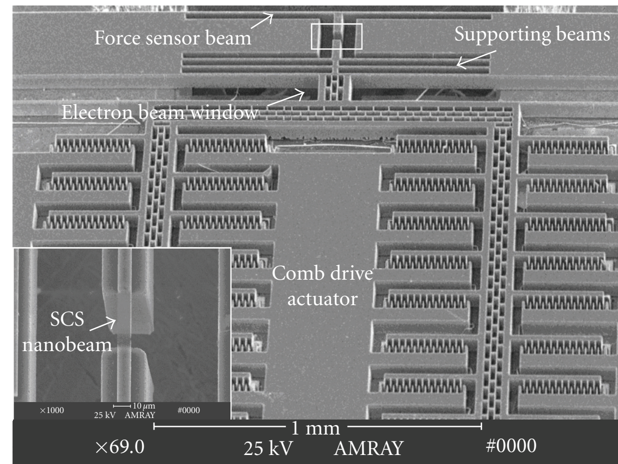


Figure 3: SEM views of the MEMS tensile-testing chip. The structures of beams and combs are shown. Inset is the enlarged view of the sample, seen through the electron beam window. The <110>-oriented SCS thin film is connected on its both ends to the supporting structures. (Reprinted with permission from [12]. 2008 IEEE).

modulus decreased monotonously as the cantilevers become thinner [10].

2.3. Tensile Tests. Among all the methods of E in nanoscale, tensile test is more challenging since the specimens must be free-standing, clamped at both ends, stretched uniaxially, and measured its elongation with nanometer resolution. To facilitate tensile testing on nanosturctures, various nanomanipulators, based on multiaxes actuation, were designed to work inside scanning electron microscope (SEM) or transmission electron microscopy (TEM). With nanostructure being stretched and tensile force being measured by nanomanipulators, sample elongation being observed by SEM or TEM, insitu tensile tests are carried out inside SEM and TEM.

By using a high-resolution TEM equipped inside with nanomanipulators for sub-nano-Newton force measurements (an AFM) and electronic conductance measurements (an STM) [13], Kizuka et al. synthesized <111>-oriented Si wires with nanometer widths inside the TEM by nanometer-tip contact and successive retraction. Then insitu tensile tests were carried out on the nanowire between two tips of AFM and STM. Figure 2 gives time-sequent series of high-resolution images of a tensile deformation process of an SCS nanowire with diameter of 4 ± 2 nm. Young's modulus was found to be 18 ± 2 GPa [11].

Micro-electro-mechanical systems (MEMSs) can be advantageously employed in the testing of nanoscale samples. It usually consists of three parts: actuator for nanomanipulating sample, sensor for measuring force on the sample, and a cofabricated (or later-attached) sample. By integrating MEMS chip in SEM or TEM, researchers have successfully performed several tensile tests on nanostructures [14–16].

We have designed and fabricated an MEMS tensile-testing chip, a TEM holder with electric terminals, and carried out insitu TEM tensile testing on SCS nanobeam [12, 17]. The holder and chip fit well in the 0.9 mm pole piece gap of JOEL 2010. The chip (5 mm × 9 mm × 0.5 mm) is fabricated by means of Si bulk micromachining and wafer bonding. Figure 3 gives the SEM view of the MEMS chip, with a sample (SCS nanobeam), a comb drive actuator, a force sensor beam, and a TEM electron beam window being integrated into it, and those parts are fabricated in one process. As the electrostatic force actuated comb drive actuator causes no current, it will cause no interference to TEM measurements.

When actuating voltage was applied, with the on-chip comb drive actuator stretching the SCS nanobeam and

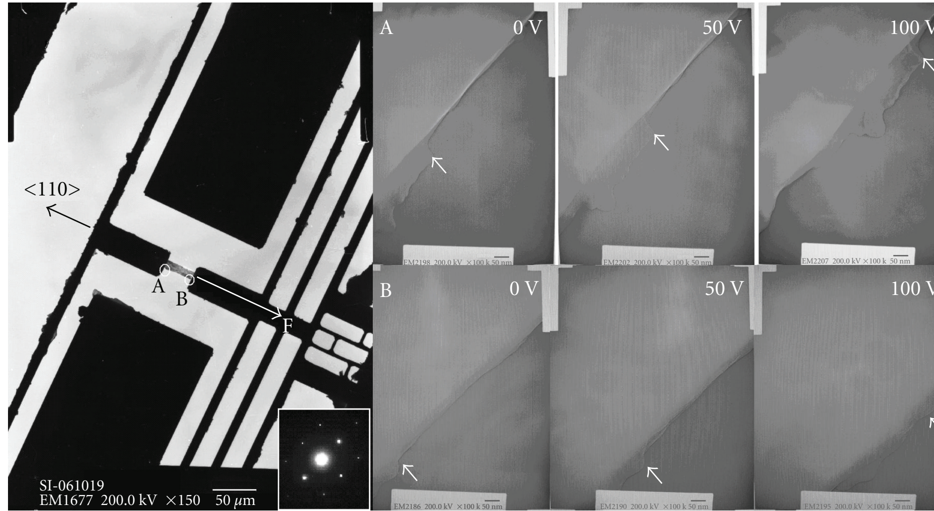


Figure 4: TEM bright field (BF) images of the structures and the SAD pattern of the SCS nanobeam (inset) TEM images of the movements of the two ends of the nanobeam, A and B (indicated by arrows). (Reprinted with permission from [12]. 2008 IEEE.)

insitu TEM observation, tensile tests are performed on the 33 μm-long 8.2 μm-broad 90 nm-thick <110>-oriented SCS nanobeam. For actuating voltages from 50 V to 100 V, incremented in 10 V steps, we snapshot the movements of the two ends of the nanobeam, A and B (indicated by the arrows), as shown in Figure 4. By taking the 4 corner marks, which were the images of 4 fixing film clamps in TEM, as reference positions, we measured the displacements l_1 (of A) and l_2 (of B). The elongation of the nanobeam Δl was l_2-l_1 and the deflection of the force sensor beam can be considered as l_1. The tensile force on the SCS nanobeam was calculated as 210 N/m $\times$ l_1, with the elastic constant of the force sensor beam being 210 N/m. By fitting the strain-stress relationship under different actuating voltages, we obtained a Young's modulus of 167 Gpa.

3. Discussion

The experimental results on Young's modulus of SCS nanobeams and nanowires are summarized in Table 1 on the catalog of their crystal directions. As the structures dimension decreasing, the resonance test shows a decreasing tendency of Young's modulus on the dimension, which is also shown clearly in Figure 5. The result of 18 GPa obtained by tensile test on an <111>-directed SCS nanowire supports this tendency too. All these suggest that for crystal silicon the size effect of E is decreasing as the dimension decreasing.

It is also interesting to note that the measured values of Young's modulus by different testing methods have a little difference. Size effect did not appear at 200 nm-thick nanobeam in bending test, while in resonance test the tendency curve indicates that it should appear at around 250 nm. As for tensile test, Young's modulus still keeps the bulk value at 90 nm-thick nanobeam.

Compared to the tensile test result, Young's modulus by resonance test shows its size effect more early. The different behaviors of E in tensile and resonance test cannot be treated as experimental error, and we think it must be surface effect working.

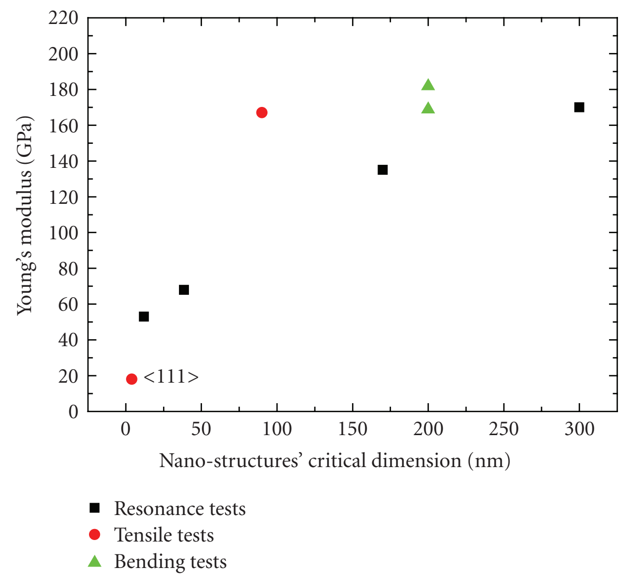


Figure 5: Values of Young's modulus versus nanostructures critical dimension, with E measured by bending, resonance, and tensile tests.

Taking nanobeam, for instance, a model to explain the difference is constructed, in which the nanobeam is treated as a composite beam with a silicon middle layer and two surface layers. The difference of Young's modulus caused by the two different methods can be described as

$$E_t - E_r = 2\left(1 - \frac{E_s}{E_0}\right)\left(2\frac{h_s}{h} - 6\frac{h_s^2}{h^2} + \frac{h_s^3}{h^3}\right)E_0, \quad (3)$$

where E_t is Young's modulus of the composite beam by tensile test, and E_r is Young's modulus by resonance test [18].

Table 1: Experimental results of E for SCS nanobeams (nanowires).

Direction	Dimension (nm) Nanobeam Width	Nanobeam Thickness	Nanowire diameter	Young's modulus (GPa)	Testing method	Reference
	200	255	—	169	Bending	[5]
	200	255	—	182	Bending	[6, 7]
	N.A.	300	—	170	Resonance	[10]
<110>	N.A.	170	—	135	Resonance	[10]
	N.A.	38.5	—	68	Resonance	[10]
	N.A.	12	—	53	Resonance	[10]
	30000	90	—	167	Tensile	[12, 17]
<100>	200	193	—	174	Bending	[8]
<111>	—	—	4	18	Tensile	[11]
N.A.	—	—	120	186/207	Bending	[9]

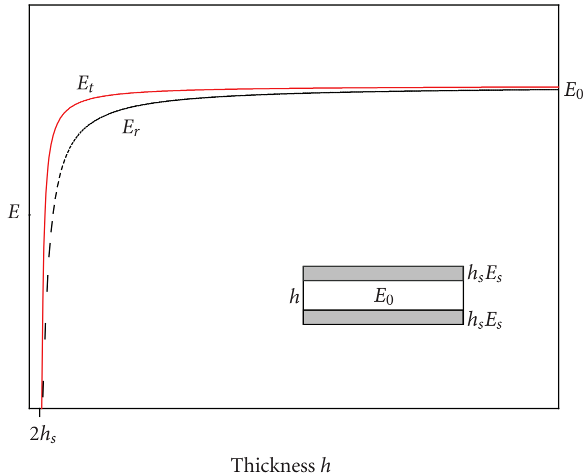


Figure 6: Illustration of the different values of E_t (in tensile test) and E_r (in resonance test) deduced from a simplified model considering nanobeam as a composite beam with two surfaces of thickness h_s and surface E_0.

Since many theoretical [19–24] and experimental results [10, 11] show that the silicon Young's modulus decreases monotonously as the SCS nanostructures dimensions decreasing, it can be deduced that $E_S < E_0$. The difference between E_t and E_r is plotted schematically in Figure 6. When h is much larger than h_s, every testing method gives a same value E_0 for Young's modulus. That is the case at macro- or microscale. As h decreases, E decreases, and the value of E by different testing methods will be different from each other. E_r shows size effect more early as h decreases, compared with E_t.

4. Conclusion

In this paper, the existing experimental tests of Young's modulus, including bending tests, resonance tests, and tensile tests, on SCS nanostructures are reviewed. The results suggest that at nanoscale, the silicon Young's modulus exhibits obvious size effect of a decreasing tendency on the nanostructures decreasing dimension. Different testing methods may give different Young's modulus values. The size effect of Young's modulus appears earlier in resonance test than in the other methods. By taking surface effect into account, this difference may be qualitatively explained for SCS nanobeam. It indicates that current experiments are still not enough to understand the behavior of SCS Young's modulus at nanoscale thoroughly, more research work should be done for it.

Acknowledgments

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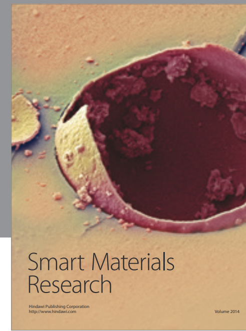
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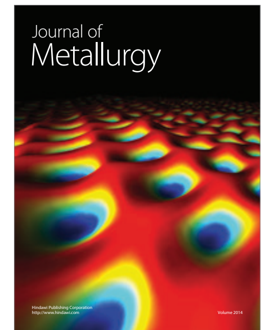
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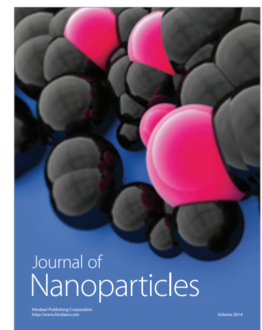
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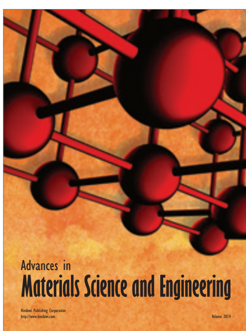
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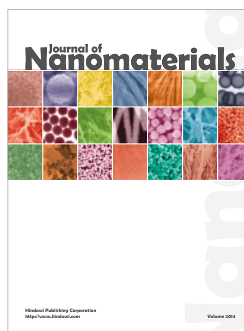
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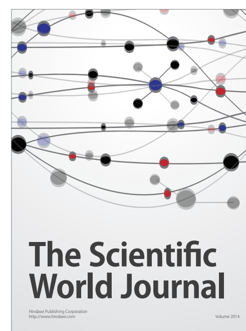
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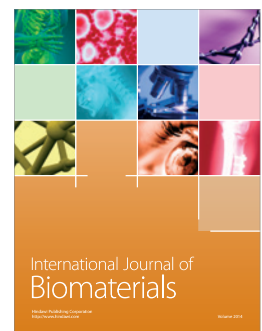
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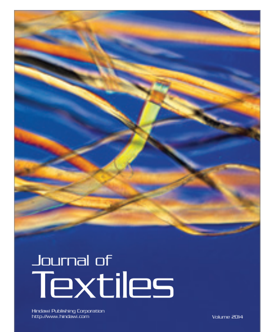
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