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Abstract
Mechanical properties of nanowires (NWs) can be different from those of their bulk counterparts, manifesting so-called size effect. Measuring their mechanical properties and understanding their deformation mechanisms are of critical relevance. This article reviews the mechanical properties of three types of NWs – metallic, ionic, and covalent NWs categorized by their bonding types – including Young’s modulus, strength, plasticity, and fracture. Major mechanical testing methods for NWs such as bending, resonance, and uniaxial tension are also summarized along with key experimental challenges such as sample preparation and effect of boundary conditions. A brief summary and outlook for future research directions are provided.

Graphical Abstract
**Key Points**

- Reviewed mechanical properties of nanowires including Young’s modulus, yield strength, plasticity, and fracture.
- Discussed the mechanical properties of nanowires based on their bonding types: metallic, ionic, and covalent bonding.
- Summarized major mechanical testing methods for NWs such as bending, resonance, and uniaxial tension as well as associated experimental challenges.
- Discussed the size effect in mechanical properties of nanowires.

**Introduction**

As fundamental building blocks of nanotechnology, a wide variety of nanowires (NWs) have emerged in the past few decades (Xia et al., 2003). These NWs exhibit unique and novel mechanical, electrical, magnetic, optical, and catalytic properties. The nanowires are used in a broad range of applications including flexible and stretchable electronics, optoelectronics, energy harvesting and storage and nanoelectromechanical systems (McAlpine et al., 2003; Wang and Song, 2006; Feng et al., 2007; Chan et al., 2008; Takei et al., 2010; Xu et al., 2011; Yao and Zhu, 2015; Yao et al., 2017, 2019; Zhou et al., 2020). For example, Ag nanowire (NW) networks are widely used as the conductive elements in flexible and stretchable electronics due to their high electric conductivity and mechanical stretchability (Lee et al., 2012; Xu and Zhu, 2012; Yao and Zhu, 2014). The operation and reliability of the NW-based devices call for a thorough understanding of the mechanical properties of NWs that can be quite different from their bulk counterparts. Size and surface effects are dominant for these small-volume materials as their characteristic dimension approaches sub-100 nm. On the other hand, as-synthesized NWs often possess well-defined internal (in contrast to surface) defects such as twinning boundaries (TBs) and stacking faults (SFs). Therefore, such NWs can be ideal model systems to probe how the defects affect the mechanical behaviors of not only NWs but also their bulk counterparts.

In this article, we focus on the mechanical properties of three types of NWs, metallic, ionic, and covalent NWs categorized by their bonding types. We start with the widely used mechanical testing methods for NWs such as bending, resonance, and uniaxial tension using atomic force microscope (AFM), scanning electron microscope (SEM), or transmission electron microscope (TEM), including key experimental challenges such as sample preparation and effect of boundary conditions. Next, the general size effect in mechanical properties at the nanoscale is briefly discussed. Then we summarize the mechanical properties of the three types of NWs measured by nanomechanical testing, including Young’s modulus, strength, plasticity and fracture. Finally, we will provide a brief summary and outlook for future research directions in this important area.

**Mechanical Testing Methods**

Mechanical testing of NWs and 1D nanostructures in general is challenging considering their miniscule size (Zhu et al., 2007; Gianola and Eberl, 2009). The available testing methods can be grouped into two main categories based on the instruments involved, AFM (Li et al., 2010) and electron microscopes including SEM and TEM (Zhu, 2016). Key developments in these two general categories of methods since the 90s are summarized in a recent review (Zhu, 2017). More specifically, the following several methods have been widely used, including resonance in SEM or TEM (Treacy et al., 1996; Poncharal et al., 1999; Chen et al., 2006a), bending using AFM (Wong et al., 1997; Song et al., 2005a; Wu et al., 2005), tension using a nanomanipulation system in SEM (Yu et al., 2000; Zhu et al., 2009), and tension using microelectromechanical systems (MEMS) in either SEM or TEM (Zhu and Espinosa, 2005; Agrawal et al., 2008; Cheng et al., 2014). Fig. 1(a)-(d) show the schematics of the four testing methods (Agrawal et al., 2011b) and Fig. 1(e) shows the SEM image of a MEMS device for tensile testing of single NWs (Zhu and Espinosa, 2005).

**Resonance**

Resonance is a simple yet widely used method to measure Young’s modulus of NWs. According to a simple beam theory, the resonance frequency of a NW is proportional to the square root of its Young’s modulus. Resonance can be excited by thermal (Treacy et al., 1996), electrostatic (Poncharal et al., 1999; Chen et al., 2006a) or mechanical (Dikin et al., 2003; Qin et al., 2012) means. The resonance test has been used to measure Young’s modulus of CNTs (Treacy et al., 1996), ZnO (Chen et al., 2006a; Qin et al., 2012), GaN (Nam et al., 2006), Si (Belov et al., 2008), B (Ding et al., 2006), and SiO₂ NWs (Dikin et al., 2003).

**AFM Bending**

AFM can be operated in four modes for mechanical characterization – (normal) contact mode, lateral force mode, nanoindentation mode, and contact resonance mode (Zhu, 2017). The first two modes are widely used in mechanical testing of NWs, in which a NW specimen is deflected by an AFM and the mechanical properties are extracted from the AFM data based on the (continuum) beam bending theory. In the contact mode, a suspended specimen is deflected vertically. It can be implemented in two ways: (1) the deflection at a particular position as
a function of the applied force, and (2) the deflection profile of the entire NW by scanning the AFM tip along its length at a constant force. The contact mode gained popularity, starting with mechanical testing of CNTs (Salvetat et al., 1999), and later for a variety of NWs such as Si, Ag, ZnO, LaB$_6$, and amorphous SiO$_2$ (Paulo et al., 2005; Jing et al., 2006; Ni and Li, 2006; Ni et al., 2006; Zhang et al., 2008).

In the lateral force mode, two common sample configurations exist, either lying on a substrate with one end pinned or suspended over a trench with both ends pinned. In this mode, the load and deflection are obtained similar to the contact mode, except using the lateral force instead of the vertical force. The lateral force mode has been used to test mechanical properties of CNTs and SiC NWs (Wong et al., 1997), Au NWs (Wu et al., 2005), Si NWs (Heidelberg et al., 2006), ZnO NWs (Wen et al., 2008) and Ge NWs (Ngo et al., 2006). In general, the contact mode has better resolution in displacement and force than the lateral force mode, but has the challenge of slippage of the AFM tip off the NW sample.

**Tension**

Tensile testing is the most popular among all the mechanical testing methods at the large scale due to its capability of measuring a wide range of mechanical properties and simplicity in data reduction. However, it is the most challenging one at the nanoscale in terms of sample preparation and high-resolution measurement of force and displacement.

Ruoff and co-workers pioneered tensile testing of individual CNTs inside SEM (Yu et al., 2000). Two AFM cantilevers (probes) were used in the test with a stiff and a compliant cantilever used as the actuator and the load sensor, respectively. Electron-beam induced deposition (EBID) of amorphous carbon was used to clamps an individual CNT at the two AFM tips. The stiff AFM cantilever (actuator) used in Ruoff’s work can be replaced with an even stiffer and sharp tungsten probe; the probe, attached to a nanomanipulator, is commonly used to manipulate 1D nanostructures. Zhu et al. used such a probe to manipulate and then conduct tensile testing of Si NWs in SEM. A compliant AFM cantilever was used as the load sensor (Zhu et al., 2009). Strain resolution of 0.03% (for a NW of 3 μm in length) and load resolution of 1 nN were achieved.

MEMS consist of micrometer-scale components but offer nanometer displacement and nano-Newton force resolutions, meeting the stringent requirements for nanomechanical testing. MEMS-based in-situ SEM/TEM testing of nanostructures (Zhu and Espinosa, 2005; Haque et al., 2011; Zhu and Chang, 2015) has received much interest. Zhu and Espinosa have developed the first MEMS stage that includes an on-chip actuator and an electronic load sensor with a gap in between (Zhu and Espinosa, 2005; Zhu et al., 2005, 2006; Espinosa et al., 2007). Two types of MEMS actuators were used, thermal actuator for displacement control and comb-drive...
actuator for force control; the electronic load sensor was based on differential capacitive sensing. A number of MEMS platforms have been developed for testing a wide variety of 1D nanostructures including CNTs and NWs (Zhang et al., 2009, 2011; Ganesan et al., 2010; Brown et al., 2011; Steighner et al., 2011; Chen et al., 2012; Tsuchiya et al., 2012; Yilmaz and Kysar, 2013).

MEMS-based in-situ TEM testing enables quantitative stress-strain measurement as well as simultaneous TEM observation of defect dynamics. This powerful experimental method, together with atomistic modeling, has significantly advanced our understanding of not only mechanical properties of NWs but also deformation mechanisms at the nanoscale (Ramachandramoorthy et al., 2015; Cheng et al., 2017; Yin et al., 2019). This makes possible employing NWs to probe important deformation mechanisms such as dislocation-twin boundary (TB) interactions, brittle-to-ductile transition, and hydrogen embrittlement; NWs are indeed an ideal probe for this purpose due to their well-controlled defect structure and small size for high-resolution TEM observation. In addition to quasistatic tensile testing, MEMS platforms have enabled a variety of advanced mechanical characterizations, such as fatigue test (Hosseini and Pierron, 2013), under displacement or force control with feedback (Li et al., 2020), different temperatures (Chang and Zhu, 2013; Chen et al., 2014), at high strain rates (Ramachandramoorthy et al., 2016; Li et al., 2020), and strain effect on electric conductivity (Bernal et al., 2014) and thermal conductivity (Murphy et al., 2014).

Sample Preparation
Manipulation and mounting of NW specimens with nanoscale resolution and high throughput is a critical step in nanomechanical testing of NWs. This step becomes particularly challenging for tensile testing. It can be achieved by "pick and place" using a manipulator inside SEM (Zhu and Espinosa, 2005). EBID of amorphous carbon or platinum is commonly employed to clamp the specimens.

Some as-synthesized crystalline NWs are vertically oriented on a substrate. Thus, direct measurement on such as-synthesized NWs could eliminate the sample preparation step and avoid ambiguous boundary condition. The lateral force mode of AFM was used to deflect vertically aligned ZnO NWs and determine the Young’s modulus (Song et al., 2005b). In addition, an electrostatic field was also used to stimulate ZnO NWs to resonance to measure the Young’s modulus (Chen et al., 2006a). These vertically aligned NWs form strong bonding with the substrate. Bending tests have been performed to determine the fracture strengths of Si NWs (Hoffmann et al., 2006).

Importance of Boundary Conditions
Uncertainty of the boundary conditions is a major challenge for nanomechanical testing, including resonance (Qin et al., 2012), AFM contact mode or lateral force mode (Chen et al., 2006b), and tension (Murphy et al., 2013). For NWs without clamps (e.g., by EBID of amorphous carbon or platinum), the boundary condition purely depends on van der Waals interactions between the sample and the substrate. Even with the clamps, they are relatively compliant compared to the NWs. To assess the boundary conditions in the AFM bending, one method is to probe the NW at multiple locations along the length to obtain the deflection profile. In the case without clamps, Chen et al. (2006b) found that for NWs with small diameters, the deflection profiles were fitted best with the fixed-fixed (doubly clamped) boundary condition; while for NWs with large diameters, the deflection profiles were fitted better with simply supported boundary condition. The stiffness of the EBID clamps was found to be comparable to that of inorganic NWs (Murphy et al., 2013). As a result, significant errors can be introduced in measurements of strain under tension tests and hence the measured Young’s modulus.

Using the resonance test, Zhu and co-workers studied the effect of clamping on the measured Young’s modulus of ZnO NWs and provided a guideline on how to obtain the “fixed” boundary condition (Qin et al., 2012). The NWs were clamped at one end by EBID of amorphous carbon for in-situ SEM resonance tests. EBID was repeated several times to deposit more amorphous carbon at the same location. The resonance frequency was found to increase with the increasing clamp size until approaching a constant value corresponding to the “fixed” boundary condition. The critical clamp size was given as a function of the NW diameter and NW Young’s modulus.

Size Effect
The surface atoms can be elastically stiffer or softer than the bulk atoms (Zhou and Huang, 2004). The softening effect is primarily due to the bond loss (i.e., loss of neighboring atoms on the surface). In contrast, the stiffening effect can be attributed to the electron redistribution (often called bond saturation) (Zhou and Huang, 2004; Shim et al., 2005). Another mechanism that contributes to the size effect in Young’s modulus of NWs, especially metallic NWs, is bulk (or core) nonlinear elasticity (Liang et al., 2005). For example, the interior compressive stress caused by the tensile surface stress in metallic NWs is large enough to induce a nonlinear increase in the Young’s modulus of the bulk atoms. Which mechanism plays a more dominant role depends on a number of factors such as the bonding type, NW diameter, axial orientation, and side surface facets (Zhou and Huang, 2004; Liang et al., 2005; Zhu, 2017). In addition, loading type plays an important role in the measured size effect in Young’s modulus. For example, if the surface elasticity is the dominant mechanism, the elasticity size effect would be manifested more strongly under bending than under tension as the surface plays a greater role during bending (Xu et al., 2010), as shown in Fig. 2 in the case of ZnO NWs (Xu et al., 2010). It is thus recommended to perform tests under different loading modes (e.g., tension and bending) to decipher the size effect in Young’s modulus (Chang et al., 2016).
Internal dislocation interaction is the dominant mechanism for plastic deformation of bulk materials. For NWs, however, dislocation nucleation from free surfaces becomes dominant (Park and Zimmerman, 2005; Park et al., 2009; Zhu and Li, 2010; Weinberger and Cai, 2012; Zhu, 2017). As a result, the yield strength is expected to show sensitive temperature and strain-rate dependence and increase modestly with the decreasing NW diameter. Fracture is typically initiated from surface flaws (defects). But reports have also shown that it is possible to initiate fracture from internal defects such as point defects (He et al., 2011). In either case, as the number of defects reduces with the decreasing NW size, the fracture strength increases.

Mechanical Properties of Metallic NWs

Metallic NWs have been synthesized by a range of methods, including the template method (Bera et al., 2004), hydrothermal method (Liu et al., 2003), electrochemical deposition (Tian et al., 2003), chemical vapor deposition (Kim et al., 2008), physical vapor deposition (Richter et al., 2009; Yoo et al., 2010), and polyol method (solution phase) (Murphy and Jana, 2002; Sun et al., 2002; Wiley et al., 2005; Wiley et al., 2007). The last two methods are known to produce high-quality single-crystalline and penta-twinned NWs, respectively, with uniform diameter, smooth surfaces, and well-defined defect structures if any (e.g., TBs). Note that a penta-twinned NW has five twin segments joined along a common quintuple line in the axial direction. It is important to emphasize that high-quality NWs are extremely important for mechanical testing because it is critical to not only measure true mechanical properties but also to understand the deformation mechanisms. Among the many metallic NWs, Ag and Au NWs have received most attention. Studies on mechanical properties of metallic NWs focus on the elastic modulus, yield strength, ultimate strength, and plasticity. This section will begin by the mechanical properties of Ag and Au NWs considering the effect of NW size (diameter), planar defects, and cross-sectional shape, followed by several other metallic NWs (e.g., Cu, Ni and Pd).

Ag NWs

Young’s modulus

The Young’s modulus of NWs has been extensively investigated by the resonance, bending, or tensile test. Most data showed a stiffening size effect in the Young’s modulus, i.e., increasing from the bulk value of 84 GPa to about 180 GPa with the decreasing diameter (Fig. 3(a)) (Cuénot et al., 2004; Jing et al., 2006; Wu et al., 2006; Filleter et al., 2012; Zhu et al., 2012; Alducin et al., 2016; Chang et al., 2016). For example, a study on penta- (or fivefold) twinned Ag NWs with <110> orientation revealed a stiffening size effect in the Young’s modulus between 34 and 130 nm in diameter (Zhu et al., 2012). The Young’s modulus continuously increased with the decreasing diameter below 80 nm and remained constant for diameter above 80 nm (close to the bulk value).

To decipher the mechanisms of the reported size effect in Young’s modulus (surface elasticity or bulk nonlinear elasticity), Zhu and co-workers tested the same Ag NWs using two different methods, in situ SEM resonance test and tensile test. It was found that some combination of bulk nonlinear elasticity and surface elasticity is responsible for the measured size effect in Young’s modulus of penta-twinned Ag NWs. In addition, the authors found a transition in the cross-sectional shape from pentagon to circle with decreasing NW diameter, which is of important relevance to quantify the size effect in Young’s modulus (Chang et al., 2016).
Twining and dislocation slip are two competitive deformation mechanisms in face-centered cubic (FCC) metals. The rivalry between the two mechanisms prevail in FCC metallic NWs, depending on the axial orientation (Schmid factor) and the generalized stacking fault energies (Weinberger and Cai, 2012). In NWs both mechanisms start with partial dislocation nucleation from free surfaces. Yin et al. (2019) recently found another factor, cross-sectional shape, may influence the competition between the two mechanisms in single-crystalline Ag NWs using in-situ TEM tensile testing and molecular dynamics (MD) simulations, as shown in Fig. 4. Twin deformation accompanied by a large plasticity occurred in NWs with low aspect ratios. With increasing aspect ratio, a transition in deformation mode from twinning to dislocation slip was observed. Theoretical and numerical studies showed that the energy barrier for twinning depends on the aspect ratio of the cross section, proportional to the change in surface energy as a result of the twinning–detwinning of the existing TB could occur (Cheng et al., 2020). The bi-twinned Ag NWs can also undergo stress relaxation, as a result of dislocation nucleation (Cheng et al., 2020). Under larger loading, the partial dislocations can transmit across the TB, leading to localized dislocation slip or necking and eventual fracture. However, when the volume ratio between the two twin variants is small, another deformation mechanism – detwinning of the existing TB – could occur (Cheng et al., 2017), which can result in the twinning behavior similar to that reported in single-crystalline Ag NWs (Yin et al., 2019).

For penta-twinned Ag NWs, stress relaxation and plastic strain recovery were also observed, similar to the bi-twinned Ag NWs but to a larger extent (Fig. 5(c) and (d)). The inhomogeneous stress field generated intrinsically by the fivefold twin structure can further drive the partial dislocations back upon unloading (Bernal et al., 2015; Qin et al., 2015). The TBs confine dislocation activities with a direct impact on ductility and strength by forming a complicated 3D dislocation structure (Filleter et al., 2012;
Narayanan et al., 2015). MEMS-based tensile testing was used to study the influence of strain rate on the deformation of Ag NWs. Brittle fracture was observed at low strain rates, while ductile fracture at high strain rates (Ramachandramoorthy et al., 2016).

Au NWs

Different from Ag NWs, the reported Young’s moduli of Au NWs are rather scattered. The average Young’s modulus of Au NWs with diameter ranging from 40 to 250 nm measured by AFM bending was 70 ± 11 GPa (Wu et al., 2005), close to the value of bulk Au (78 GPa). Resonance tests of single crystalline <100> Au NWs found a decrease in Young’s modulus with decreasing NW diameter (Petrova et al., 2006).

For yield strength and UTS of Au NWs, size effect was widely reported. As shown in Fig. 6(a), an increase in the yield strength from 200 MPa – bulk value of the yield strength – to as high as 8 GPa with a reduction of diameter from 300 to 40 nm was reported (Wu et al., 2005; Lu et al., 2011; Seo et al., 2011; Sedlmayr et al., 2012; Wang et al., 2013). Single crystalline Au NWs, synthesized by physical vapor deposition, exhibited large plastic deformation as a result of coherent twin propagation as revealed by in-situ SEM tensile tests (Seo et al., 2011; Sedlmayr et al., 2012). The flow stress increased with the decreasing NW diameter (Seo et al., 2013). The twinning-induced plastic deformation was reversible through a detwinning process under cyclic loading (Lee et al., 2014). A size-dependent transition from dislocation plasticity to deformation twinning was observed in Au NWs (Hwang et al., 2015). In addition to size, the transition was found to depend on the aspect ratio of the NW cross section, similar to the case of Ag NWs (Yin et al., 2019). For <111> oriented Au NWs with angstrom-scale twins (TBs perpendicular to the NW axial direction), UTS was found to approach the theoretical limit (Wang et al., 2013).

Other Metallic NWs

For metallic NWs, the elastic deformation is limited by the dislocation nucleation. Since single crystalline NWs are free of defects and large surface to volume ratio so they can sustain much higher elastic strain than the bulk ones. As a result of size reduction, a transition from ductile to brittle fracture in metallic NWs was found (Richter et al., 2009). When the Cu NW diameter decreased
from 300 to 75 nm, the tensile strength increased from 1 to 7 GPa, where the Cu NWs were synthesized by physical vapor deposition along $<110>$ direction. Fig. 6(b) summarizes the strength data of the Cu NWs and the microwhiskers tested by Brenner back in the 50 s (Brenner, 1956). The critical resolved shear stress of single crystalline Ni NWs was shown to increase with the decreasing nanowires diameter (Peng et al., 2012). By electrochemical deposition on nanoporous anodic aluminum oxide (AAO) templates, Ni NWs with varying diameters (100–300 nm) were synthesized. In-situ SEM tensile tests were used to investigate the size and strain-rate dependency on the yield strength of $<111>$ and $<112>$ oriented Ni NWs. The yield strength increased from 1.2 to 3.4 GPa as the diameter decreased from 300 to 80 nm, while increased from 2 to 3 GPa as the strain rate increased from $10^{-4}$ to $10^{-3}$ s$^{-1}$ for Ni NWs of 100 nm in diameter (Peng et al., 2013).

Pd NWs, synthesized by physical vapor deposition ($<110>$ oriented), displayed nonlinear elasticity beyond 1% strain. The Young’s modulus increased from 120 GPa for NWs larger than 100 nm in diameter to 290 GPa for NWs of 33 nm in diameter from in-situ SEM tensile testing (Chen et al., 2012). As the diameter of the single crystalline Pd NWs decreased from 260 to 40 nm, the yield strength increased from 1 to 4 GPa. While it is generally known that the tensile stress required to nucleate partial dislocations from the surface increases as the NW diameter decreases, Chen et al. reported that defect-free Pd NWs exhibit an apparent stochasticity in the measured strength of dislocation nucleation, which was attributed to a thermally activated deformation process (Chen et al., 2015). This work, along with others, revealed that the yield strength only shows a modest size effect in defect-free NWs.
The authors hypothesized that diffusion of point defects is the origin of the surface dislocation nucleation. The exact nature of the diffusion process and its influence on dislocation nucleation, however, remain elusive and warrant further investigation.

**Mechanical Properties of Ionic NWs**

**ZnO NWs**

**Young's modulus**

Due to the large exciton binding energy and wide bandgap, ZnO is an important semiconducting, piezoelectric and biocompatible materials (Wang, 2003). The Young's modulus of ZnO NWs has been extensively investigated, as summarized in Fig. 7(a). AFM based lateral bending of vertical aligned ZnO NWs showed that the Young's modulus of ZnO NWs with an average diameter of 45 nm is $29 \pm 8$ GPa (Song et al., 2005b), which is significantly lower than the bulk value (140 GPa). Wen et al. reported that Young's modulus of ZnO NWs is independent of diameter and close to the bulk value, for the NWs ranging from 18 to 304 nm in diameter. However, Chen et al. (2006a) reported a size dependence of Young's modulus in [0001] oriented ZnO NWs using electric-field-induced resonance in SEM. The measured values were up to 220 GPa for diameter of $17$ nm. Agrawal et al. (2008) reported a similar size effect using in-situ TEM tension testing, which was supported by their MD simulations. Xu et al. conducted in-situ SEM tension and buckling test on the same [0001] ZnO NWs and found that the tensile modulus and bending modulus increased when the NW diameter decreased from 80 to 20 nm. Interestingly, the bending modulus increased faster than the tensile modulus, indicating that the elasticity size effect in ZnO NWs is mainly due to surface stiffening. A core-shell model based on continuum mechanics was used to fit the experimental data well (Xu et al., 2010).

**Fracture strength**

Size dependency of the fracture strength of ZnO NWs has been reported, see Fig. 7(b). Desai et al. reported a considerable increase in the fracture strength from 5 to 15 GPa with a decrease in NW diameter from 500 to 200 nm (Desai and Haque, 2007). Xu et al. (2010) found a similar rise in strength from 4 to 10 GPa when the NW diameter decreased from 90 to 20 nm. According to Agrawal et al. (2008) and Wen et al. (2008) a diameter decrease from 500 to 20 nm resulted in a rise in the fracture strength from 3 to 10 GPa. Tensile and bending measurements were used to determine the fracture strength of [0001] oriented ZnO NWs vertically synthesized on a sapphire substrate, with diameters ranging from 60 to 310 nm (Hoffmann et al., 2007). The tensile strength was 3.7–5.5 GPa, while the bending strength was found to be approximately twice as large as the tensile fracture strength.

To understand the size effect in the fracture strength, two hypotheses, based on surface flaws and internal defects (point defects), have been proposed. According to Weibull statistics, a correlation between the surface area and the fracture strength was identified, implying that surface flaws are responsible for the NW fracture (Agrawal et al., 2008). However, He et al. (2011) found a
correlation between the volume and the fracture strength, also using Weibull statistics, which indicates that the NW fracture is due to internal (volume) defects. The authors used in-situ cathodoluminescence (CL) analysis to confirm the presence of vacancies in the ZnO NWs. The fracture behavior of ZnO NWs is possibly a result of both surface defects and internal point defects. However, quantifying the contribution of each type of defect remains challenging due to the difficulty of quantifying the density and distribution of such defects, particularly point defects. A potential method is atom probe tomography (APT) that can determine the density and distribution of point defects down to the single-atom level. APT’s local electrode atom probe (LEAP) technology has been demonstrated on single NWs (Agrawal et al., 2011a).

Anelasticity

Zhu and co-workers et al. discovered a giant anelasticity in ZnO and doped Si NWs using in-situ SEM bending tests. For a single NW, upon removal of the bending load, a substantial portion of the total strain gradually recovers following instantaneous recovery of the elastic strain (Cheng et al., 2015). Such an anelasticity was attributed to point defect diffusion in an inhomogeneous strain field. The presence of point defects was confirmed by the electron energy loss spectroscopy. This work is another manifestation that point defects could play an increasingly important role on the mechanical properties of nanostructures.

GaN and GaAs NWs

Gallium nitride (GaN), a significant semiconductor with a wide direct band gap of 3.4 eV at room temperature, is of particular interest due to its potential application in blue and ultraviolet light emitters as well as high temperature and high power optoelectronic devices (Liu et al., 2005). Nam et al. (2006) determined the diameter-dependent Young’s modulus of GaN NWs via in-situ electromechanical resonance tests in TEM. The measured Young’s modulus was close to the theoretical value of bulk GaN (300 GPa) at the largest diameter studied (84 nm) and steadily decreased with the decreasing diameter. Planar defects such as SFs were found to influence the Young’s modulus of GaN NWs considerably (Dai et al., 2015). The tensile fracture strength of GaN NWs was determined to be in the region of 4–7 GPa using MEMS tensile testing (Brown et al., 2011). Cyclic tensile tests found that single crystalline GaN NWs were capable of withstanding uniaxial strains of at least 0.01 and up to 0.04.

Using in-situ TEM compression test, Wang et al. studied the mechanical behavior of vertically aligned single crystalline <111> -oriented GaAs NWs grown on a GaAs substrate (Wang et al., 2011). For GaAs NWs with diameters ranging from 50 to 150 nm, the elastic strain limit was found to be 10%–11%. When the diameter was less than 25 nm, the GaAs NWs exhibited obvious plastic deformation. The Young’s modulus of the NWs increased noticeably as the NW diameter decreased. The Young’s moduli of GaAs NWs with two distinct structures, defect-free single crystalline wurzite and defective wurzite containing a high density of SFs, were investigated. The presence of a high density of SFs was found to increase the Young’s modulus by 13% (Chen et al., 2016).
Mechanical Properties of Nanowires

Si NWs

**Young's modulus**

Si is one of the most important materials in the semiconductor and MEMS industries. Si NWs exhibits unique mechanical, electrical, and optical capabilities with potential applications in mechanical oscillators, sensors, field effect transistors, photovoltaics, and lithium ion batteries. Young's modulus as a function of diameter for Si NWs size is summarized in Fig. 8. Li et al. (2003) reported a size effect on Young's modulus of single crystalline silicon cantilevers (12–170 nm) by resonance measurement; Young's modulus decreases monotonously as the cantilevers becomes thinner. Zhu et al. (2009) reported stress–strain measurements of Si NWs (diameter range 15–60 nm) using in-situ SEM tensile testing. The Si NWs were synthesized using the vapor-liquid-solid (VLS) mechanism. When the diameters of Si NWs were larger than 30 nm, the Young's modulus was close to the bulk value (e.g., 187 GPa for <111> orientation). However, when the diameters were less than 30 nm, the softening tendency became clear, i.e., the Young's modulus decreases with the decreasing NW diameter. On the other hand, some studies reported a stiffening effect with the decreasing diameter (Tabib-Azar et al., 2005; Gordon et al., 2009; Tsuchiya et al., 2018). In addition to surface elasticity, the observed size effect in Young's modulus could be related to the presence of native oxide and surface imperfections.

**Fracture**

Numerous studies have been reported on the fracture strength of Si NWs. In general, fracture strength of Si NWs increases as the diameter decreases as shown in Fig. 8(b) (Pearson et al., 1957; Johansson et al., 1988; Nakao et al., 2006; Zhu et al., 2009; Zhang et al., 2010; Kim et al., 2011; Steighner et al., 2011; Tang et al., 2012; Wagner et al., 2015). Zhu et al. (2009) found that the fracture strength increases from 5.1 to 12.2 GPa and fracture strain increases from 2.7% to about 12%, as the NW diameter reduces from 60
to 15 nm. The measured value is close to the theoretical values of 15.2 and 18.8 GPa for Si in the \( \langle 110 \rangle \) and \( \langle 111 \rangle \) directions, respectively. The fracture of Si NWs was attributed to the surface flaws. Hoffmann et al. (2006) measured the bending strength of VLS-synthesized \( \langle 111 \rangle \)-oriented Si NWs with diameters between 100 and 200 nm. The maximum bending strain before fracture was 6%, corresponding to a fracture strength of 12 GPa.

Brittle to ductile transition (BDT) has been extensively studied for bulk Si. However, it remains unclear how BDT in Si NWs is affected by the NW size and in particular if Si NWs become ductile at room temperature. A number of studies showed that Si NWs behave linear elastically until brittle fracture under tension (Gordon et al., 2009; Zhu et al., 2009; Tang et al., 2012; Zhang et al., 2016); by contrast, a few studies demonstrated that Si NWs could exhibit substantial plastic deformation under tension (Han et al., 2007) and especially under bending (Tang et al., 2012; Kang and Saif, 2013). Cheng et al. (2019) found that Si NWs are brittle at room temperature but exhibits ductile behavior with dislocation-mediated plasticity at elevated temperature by in-situ temperature-controlled nanomechanical tensile testing in TEM. 78 Si NWs were tested between room temperature and 600K, which revealed that unconventional \( \frac{1}{2} \langle 110 \rangle \) \{001\} dislocations become highly active with increasing temperature, resulting in the transition from brittle fracture to dislocation-mediated plasticity and ductile fracture at elevated temperature, as shown in Fig. 9.

**SiC NWs**

Utilizing AFM-based bending tests, Wong et al. (1997) first reported the fracture strength of SiC NWs. The maximum fracture strength of SiC NWs was 53.4 GPa, significantly higher than the values reported for bulk SiC and microscale SiC whiskers. Han et al. (2005) examined the plastic deformation behavior of intrinsically brittle SiC NWs by high resolution TEM. The plastic deformation was attributed to localized lattice bending, atomic lattice disordering, and amorphization.
Cheng et al. (2014) reported the effect of size-dependent defect density of SiC NWs, consisting of pure 3C structure, 3C structure with an inclined SF, and highly defective structure. The SiC NWs, $<111>$-oriented, were synthesized by high-temperature thermal evaporation through the VLS process. In contrast to previously observed superplasticity, SiC NWs were found to fail in brittle fracture at ambient temperature (Fig. 10(a)). It is worth noting that cracks originate and propagate in the 3C segments with the 19.47° SFs, rather than in the highly defective segments. The size effect on the fracture strength of SiC NWs was related to the size-dependent defect density (i.e., the 3C structure with 19.47° SFs) (Fig. 10(b) and (c)). Internal structures and flaws are frequently present in both bottom-up and top-down produced crystalline NWs (in addition to free surfaces). This work emphasizes the critical importance of closely examining the interior structures and flaws of such NWs and their effect on the nanomechanical behavior. The fracture strength of SiC NWs displayed a strong size effect; that is, the fracture strength increased up to over 25 GPa with the decreasing diameter, close to the theoretical strength of 3C SiC (Fig. 10(d)).

**Summary and Outlook**

This article summarizes recent advances in the mechanical properties of NWs. Almost all the methods for mechanical characterization of NWs use different types of microscopes (TEM, SEM, or AFM) as a platform for seeing, manipulating, deforming and measuring the properties of NWs. Many aspects of the mechanical properties of NWs have been investigated, including elasticity, fracture, plasticity, and anelasticity, often in combination with atomistic simulations. In particular, significant progress in the experimental mechanics of NWs has been made possible by in-situ TEM testing, which enable direct dynamic observation of deformation processes and concurrent recording of stress–strain curves. Free surfaces and often times interior defects were shown to have a significant impact on the mechanical properties of NWs.

**Fig. 10** (a) Representative tensile stress–strain curves of SiC NWs. (b) Defect density as a function of NW diameter. Here 90° and 19.47° defects refer to highly defective structures and 3C structures with a 19.47° SFs, respectively. (c) High-resolution TEM image of the fracture surface of a SiC NW. (d) Fracture strength of SiC NWs and whiskers as a function of the diameter. Reproduced from (d) Cheng, G., et al., 2014. Mechanical properties of silicon carbide nanowires: Effect of size-dependent defect density. Nano Letters 14 (32), 754–758. Available at: https://doi.org/10.1021/nl404058r.
It is worth noting that much of the early work on mechanical property measurements revealed significant scatter and discrepancy, which is understandable given the field’s infancy, the challenge of conducting such measurements, and the possibility of differences in the synthesis methods and hence the shape and microstructures of NW samples. For instance, the NW cross section may change with diameter, which may have a significant effect on the mechanical properties measured (Chang et al., 2016). For this consideration, this article concentrates on representative data and underlying mechanisms. With continued advance in testing methods and careful consideration of the factors mentioned above, more consistent testing results have been and will continue to be obtained. For example, efforts have been taken on systematic examination of the effects of sample cross sections (Chang et al., 2016) and microstructures (Wang et al., 2013; Bernal et al., 2015; Qin et al., 2015), loading modes (Xu et al., 2010; Chang et al., 2016), and boundary conditions (Qin et al., 2012; Murphy et al., 2013).

Along with measurements of the basic mechanical properties (e.g., Young’s modulus, yield strength, and fracture strength), advanced behaviors and deformation processes of NWs have gained increasing interest in recent years. Advanced behaviors are those that are dependent on the testing temperature, rate, time, and environment, among other variables, which are of direct relevance to applications of NWs. For example, hydrogen embrittlement of Ag NWs has been probed, which revealed that hydrogen can suppress the dislocation nucleation from NW surfaces, responsible for the observed hydrogen embrittlement (Yin et al., 2019). Multiphysical properties of NWs are of increasing interest. Given the large elastic strain range of NWs, they are ideal candidates to tune other properties (e.g., electric, thermal, optical, catalytic) using elastic strain. MEMS-based techniques, due to their precise control, integrated actuation and sensing, multifunctionality, and compatibility with imaging tools like TEM, have shown promising potential in characterizing such advanced mechanical behaviors, deformation processes, and multiphysical properties.

With their outstanding mechanical properties, NWs have found a wide spectrum of applications related to the mechanical properties, such as flexible and stretchable electronics (Javey et al., 2007; McAlpine et al., 2007; Takei et al., 2010; Xu et al., 2011; Xu and Zhu, 2012; Zhou et al., 2020), nanocomposites (Yang et al., 2005), nanoelectromechanical systems (Li et al., 2007; He et al., 2008; Feng et al., 2010), energy harvesting (Law et al., 2005; Wang and Song, 2006; Boukai et al., 2008; Hochbaum et al., 2008), and energy storage (Chan et al., 2008; Huang et al., 2010). Understanding the mechanical properties plays a critical role in the reliability of such applications. Large-scale applications with NWs as the building blocks must be rigorously pursued in order to maintain the high level of interest in NWs and fulfill their promising potential. On the other hand, operation and reliability of such applications require further understanding of mechanical properties of NWs especially under different service conditions such as cyclic loading, high rate, high temperature and extreme environment.

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