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Grain boundary ridges slow dawn grain boundary motion: In-situ observation

Vera Sursaeva [a,*], Alena Gornakova [a], Faina Muktepavela [b]

[a] Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia
[b] Institute of Solid State Physics University of Latvia, Kengaraga 8, LV1063 Riga, Latvia

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ABSTRACT

The impact of grain boundary (GB) ridge on motion of high-angle GB in Zn was studied. The steady-state motion of faceted GB half-loop with $[10\bar{1}0]$ tilt GB and GB ridge was recorded in-situ. The temperatures of faceting–roughening transition were experimentally defined for three GB half-loops. Above the transition temperature GB half-loops had GB “rough-to-rough” ridge with continuously curved GB segments. Below the transition temperature a facet appeared and coexisted with two “facet-to-rough” ridges. For the first time we could extract mobility of “rough-to-rough” and “rough-to-facet” ridges and bring out clearly that GB ridge slows down GB motion. Present removes contradiction between high facet mobility and the low mobility of faceted GB.

1. Introduction

Among GB defects (GB triple junctions, GB quadruple junctions and GB facets) there is the least investigated GB defect – the GB ridge. The concept of GB ridges was developed by Cahn and Hoffmann in 1974 [1]. They proved that two curved surfaces may intersect along a line where the GB plane changes discontinuously. This line is called a first-order “rough-to-rough” ridge. A classification of various GB ridges is given in Ref. [2]. As much as GB migration can be affected by triple junctions and facets, a GB ridge may also considerably modify the kinetics of GB motion. The steady-state motion of a special 30° $[10\bar{1}0]$ tilt GB half-loop with ridge of the first order was studied and a theory of steady-state motion of a GB half-loop with a ridge is presented in [3]. For the first time mobility and activation enthalpy of the “rough-to-rough” GB ridge motion have been measured at relatively low temperatures.

It is known that strong inclinational anisotropy of GB energy leads to the phenomenon of GB faceting; faceting–roughening transitions may occur on GB [4]. The influence of a facet on the curvature-driven steady-state motion of GB in Zn bicrystal has been investigated in [5]. The normalized facet mobility m_f/m_b, where m_f and m_b are GB facet mobility and GB mobility, taken from the experimental data is presented. High facet mobility (10^{-7} m^2 s^{-1}) coexists with low mobility of GB half loop with this facet (10^{-9} m^2 s^{-1}). It is surprising result. The major goal of the current study is to show that the first-order ridges can control and slow down GB motion.

2. Experimental

In this paper we would like to demonstrate the GB ridge effect on GB motion in the simplest possible situation. We prepared three bicrystals with $[10\bar{1}0]$ tilt GB in half-loop form. (Figs. 1 and 2). There were different facets and different ridges on the tip of half-loops. The Zn flat bicrystals with $[10\bar{1}0]$ tilt GB were grown from Zn of 99.999 wt% purity using a modified Bridgman technique [3]. Flat and curved GB segments were everywhere perpendicular to the surface of the sample. Facet was flat with θ inclination to straight segments of GB half-loop. The $[10\bar{1}0]$ axes in both grains were also perpendicular to the surface of the bicrystals. The misorientation angles of bicrystals were 32°, 34° and 36°. The “special” GB with reciprocal density of coincidence sites $\Sigma = 15$ is located for misorientation angle 29.9 ± 0.2°. “Special” GB demonstrates high mobility and faceting ability. The misorientation angles in grown bicrystals are near “special” misorientation angle. Therefore GBs with misorientation angle 32°, 34° and 36° demonstrated high mobility and faceting ability too. The facets in grown bicrystals were different, facet inclination θ to straight segments of GB half-loop were 76°, 82° and 69° for bicrystals with misorientation angle 32°, 34° and 36°, respectively. Facets in different bicrystals form different angles with respect to straight GB segments. It means that those segments possess different crystallographic orientation. The c/a ratio of the lattice spacing a in the basal plane (0001) and c perpendicular to

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[*] Corresponding author. Tel.: +79163073145.
E-mail address: sursaeva@issp.ac.ru (V. Sursaeva).

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(0001) is irrational in Zn. Therefore, exact coincidence site lattices exist in Zn only for GBs with [0001] rotation axis. In all other cases, including $[10\bar{1}0]$ tilt GBs, a so-called constrained coincidence site lattice (CCSL) exists [6]. Evidently, the sites of both lattices in bicrystlas will not coincide exactly, and the difference may reach a few per cent of the lattice spacing. Moreover, in our experiments the misorientation angle is close but not equal to the misorientation of exact coincidence although still inside the range for special GBs. One has to bear in mind that the *c/a* ratio in Zn is temperature dependent. According to this argumentation we do not see the sense to characterize the facets by crystallographic orientation. The system tries to reduce free energy to relative minimum at every moment of motion choosing crystallographic orientation of facets. The misorientation angles in grown bicrystals are near "special" misorientation angle. Therefore GBs with misorientation angle 32°, 34° and 36° demonstrated high mobility and faceting ability too. The behavior of the GB system in the temperature range 380–410 °C was studied in situ in a high temperature add-on of a light microscope using polarized light. Temperature was stabilized with an error ±0.5 °C. Temperature steps between isothermal anneals were 5 or 10 °C. The duration of isothermal anneals was 20–120 s. By the transition from one constant temperature to another, the "new" temperature of the high temperature add-on and sample stabilized in few seconds. The GB shape was recorded in the course of experiment by a color video camera connected with the microscope and a computer. Facets appeared as straight GB segments on half-loop tip in an optical micrograph. The indications of the GB faceting–roughening were observed when the edges of the facets become smoother with increasing temperature and sharper with decreasing temperature.

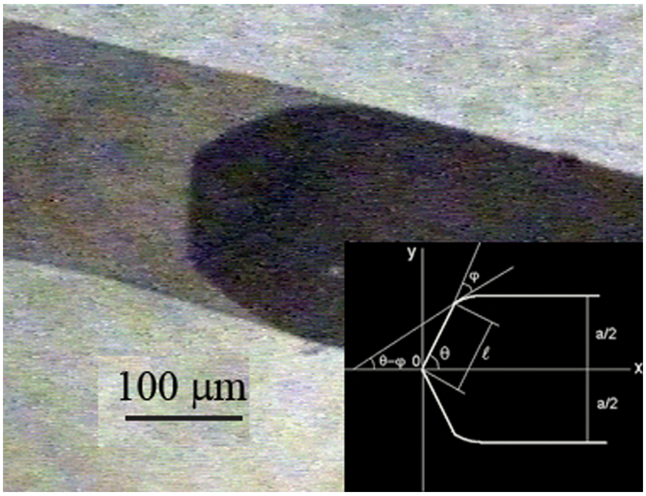

Fig. 1. Micrograph of GB half-loop with facet and two "facet-to-rough" ridges. Geometry according to [3].

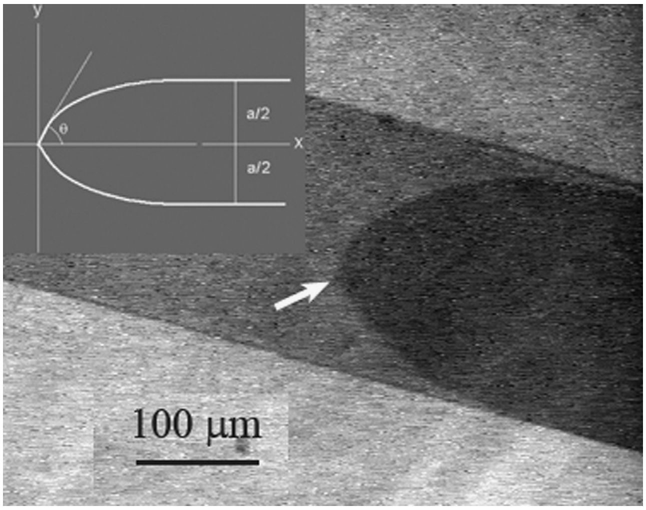

Fig. 2. Micrograph of GB half-loop with "rough-to-rough" ridge. Geometry according to [3]. "Rough-to-rough" ridge on micrograph is shown by indicator.

3. Results and discussion

The behavior of the GB system with facet and ridges was studied. At high temperatures (higher than 400 °C) the moving GB half-loop comprised only "rough-to-rough" ridge with curved segments. Facet formation on a moving half-loop was observed during cooling (from 400 °C). Development of the moving GB half-loop occurred as appearance of single facet with two "facet-to-rough" ridges. A further increase in temperature led to the disappearance of the facet with two "facet-to-rough" ridges and formation of a "rough-to-rough" ridge again. It should be noticed that all GB transitions between the observed configurations were reversible. At first the temperature of faceting–roughening transition of migrating GBs was experimentally determined as 400 °C, 393 °C and 396 °C for GBs with misorientation angles 32°, 34° and 36°, respectively (Table 1). For example, for misorientation angle 34° the facet length decreased upon heating from 380 °C, and temperature of roughening transition was observed at $T=393$ °C; i.e., the facet disappeared at 393 °C. The facet length increased upon cooling from 400 °C, and temperature of faceting transition was observed to be $T=393$ °C; i.e., the facet appeared. Below and above $T=393$ °C, the migrating GB contained and missed a facet. Above $T=393$ °C the migrating GB has no facet and below this

Table 1
Parameters of GB system motion.

Type of $[10\bar{1}0]$ tilt GB (deg)	Misorientation angle 32	Misorientation angle 34	Misorientation angle 36
Facet inclination angle θ to straight segments of GB half-loop (deg)	78	82	69
Angle φ defines the difference between surface tension of the facet	35	64	72
and the curved GB (deg)	55	52	23
Ridge vertex angle θ (deg)	57	47	50
Temperature of GB faceting–roughening transition (°C)	400	393	396
Temperature of GB motion (°C)	405	400	399
Faceted GB mobility m_f ($m^2 s^{-1}$)	4.10×10^{-10}	1.20×10^{-11}	1.60×10^{-10}
Rough GB mobility m_b ($m^2 s^{-1}$)	1.49×10^{-9}	9.46×10^{-11}	1.20×10^{-9}
For moving "facet-to-rough" ridge at facet disappearance	3.6	2.7	0.5
$\Lambda_r = \frac{m_r a}{m_b} = \frac{\theta - \phi}{\cos\ \theta \cdot\ \cos\ \phi}$	2.8	3.5	2.4
For moving "rough-to-rough" ridge $\Lambda_r = \frac{m_r a}{m_b} = \frac{\theta}{\cos\ \theta}$	1.8	1.2	1.3
$m_{r,}$ "facet-to-rough" ridge mobility, $m^3 J^{-1} s^{-1}$	1.44×10^{-3} ($\Lambda_r=3.6$)	0.85×10^{-3}($\Lambda_r=2.7$)	0.25×10^{-3}($\Lambda_r=0.5$)
	1.12×10^{-3} ($\Lambda_r=2.8$)	1.10×10^{-3}($\Lambda_r=3.5$)	1.20×10^{-3}($\Lambda_r=2.4$)
$m_{r,}$ "rough-to-rough" ridge mobility,$m^3 J^{-1} s^{-1}$	1.05×10^{-3} ($\Lambda_r=1.8$)	0.60×10^{-4}($\Lambda_r=1.2$)	6.50×10^{-4}($\Lambda_r=1.3$)