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# The influence of electronic transport across interface junction between Si substrate and the root of ZnO micro-prism on field emission performance*

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ZnO micro-prisms are prepared on the p-type and n-type Si substrates, separately. The $I$–$V$ curves analysed by AFM show that the interface junctions between the ZnO micro-prisms and the p-type substrate and between the ZnO micro-prisms and the n-type Si substrate exhibit p–n junction behaviour and ohmic contact behaviour, respectively. The formation of the p–n heterojunction and ohmic contact is ascribed to the intrinsic n-type conduction of ZnO material. Better field emission performance (lower onset voltage and larger emission current) is observed from an individual ZnO micro-prism grown on the n-type Si substrate. It is suggested that the n-Si/n-ZnO interfacial ohmic contact benefits the electron emission; while the p-Si/n-ZnO interface heterojunction deteriorates the electron emission.

**Keywords:** field emission, interface junction, p-n junction, ohmic contact
**PACC:** 7970, 8160C, 6150C

## 1. Introduction

Field emission is one of the fascinating properties of one-dimensional structures due to their high aspect ratios. In virtue of the potential applications in the flat panel displays,[1] electron microscopes,[2] and microwave devices,[3] researches on field emission have been extensively carried out in several fields, such as nanotubes,[4] nanowires[5] and nanorods,[6] etc. The low electron affinity, chemical inertness, thermal stability and wide band gap of ZnO hint that it may be a promising candidate as an electron emitter material. The studies[7,8] have proved that the ZnO 1D materials can easily achieve 1mA/cm$^2$ emission current density that is the minimum value to produce 300cd/m$^2$ luminance for video graphics array (VGA) display at a low field. The eximious properties and promising applications of ZnO material attract tremendous attention to its field emission behaviour. In order to obtain the better field emission performance (large emission current density at a low applied field), many groups have studied the influences of absorbate,[9] chemical doping,[10] and morphology[11] on the field emission behaviour. However, there are few reports addressing the influence of substrate on the field emission behaviour.

In this paper, we investigate the influence of interface junction between the roots of ZnO micro-prisms (ZOMPs) and the Si substrate on the field emission behaviour from ZOMPs. The ZOMPs were synthesized on p-type and n-type Si substrates, separately. Field emission measurement of single ZnO micro-prism was performed in atomic force microscope (AFM) configuration. By comparing the field emission data, it is found that the ZOMP grown on the n-type Si substrate exhibits the better electron emission performance than on the p-type Si substrate. Namely, the interface junction between the ZOMP and substrate plays an important role in determining the field emission property.

## 2. Experiment and results

The ZOMP arrays were prepared by catalyst-free

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chemical vapour deposition (CFCVD). The Zn powder with purity of 99.99% and Si substrate were placed at the bottom and the open end of an inner tube, respectively. On purpose to investigate the influence of interface junction between emitter material and Si substrate on field emission, two p-type and n-type Si wafers were used as substrates. Both of the silicon substrates ($8 \times 8$mm) were subject to ultrasonic-cleaning in ethanol and deionized water, and then to drying by $N_2$ in sequence. Oxygen was introduced into the deposition chamber at a fluence of 10 sccm when the temperature reached 500°C. Oxygen and Zn vapours converged on the substrates because of the circumfluence of oxygen gas; as a result, grey products were observed after deposition. Observation of morphology was performed using a scanning electron microscope (SEM, JEOL-6360LV). *I-V* characteristic and field emission were investigated by using an atomic force microscope (AFM, SPI3800-SPA300HV).

Scanning electron microscopic images reveal the general morphology of highly dense and well-aligned ZOMP arrays. The images in Figs.1(a) (Low magnification) and (b) (high magnification) are the bird's eye view of ZnO microstructures grown on the p-type Si substrate, while the images in Figs.(c) (Low magnification) and (d) (high magnification) are the oblique view of the ZnO microstructures grown on the n-type Si substrate. The well-faceted hexagonal cross-sections of the individual ZOMPs were observed to have diameters in the 1–2$\mu$m range in the products on both p-type and n-type Si substrates.

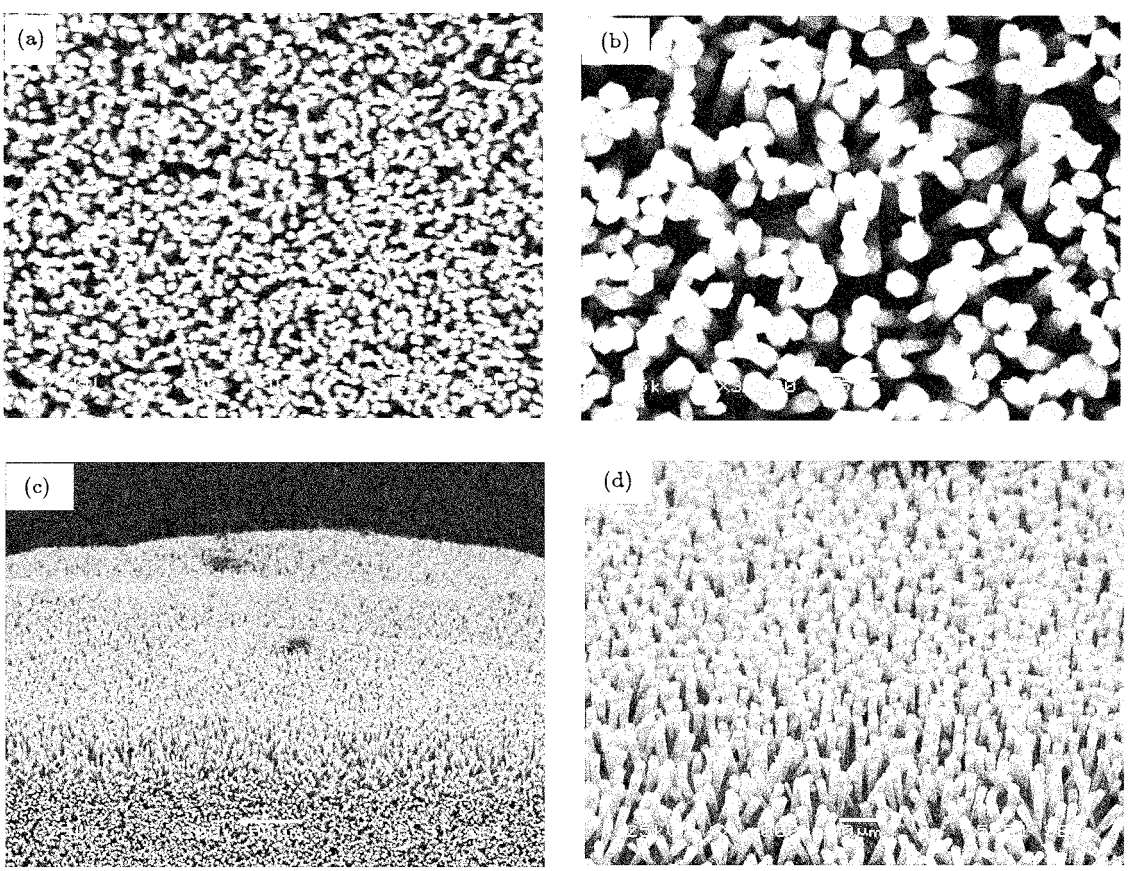



**Fig.1.** Scanning electron microscopic images of ZnO micro-prisms. Images (a) and (b) are bird's eye view of ZOMPs grown on a p-type Si substrate; Images (c) and (d) are the oblique view of ZOMPs grown on an n-type Si substrate.

Prior to measuring the electrical characteristics, the topographies of ZOMP arrays were obtained using an AFM contact mode. Figures 2 (a) and (b) show the topographies of ZnO microstructures on the p-type and n-type Si wafers. One can find that the diameters of ZnO micro-prisms range from 1–2$\mu$m for both samples, which is in accord with the observation of SEM. No obvious convolution effect in imaging was observed as reported by Park *et al*,[12] which may be related to the large diameters and flat tops of ZOMPs.

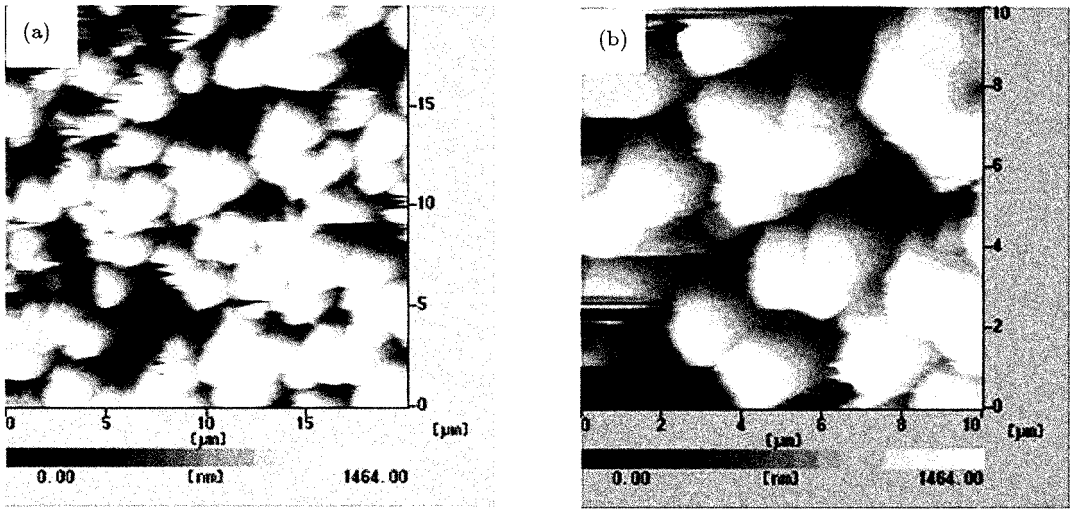



**Fig.2.** AFM images of ZOMPs grown, separately, on a p-type Si substrate (a) and on an n-type Si substrate(b). The diameters of ZOMPs grown on both p-type and n-type substrates range from 1–2$\mu$m.

*I-V* characteristic measurements of the interface junction between the Si substrate and a single ZOMP were conducted in AFM configuration. To avoid the formation of Schottky barrier between the top of ZOMP and AFM tip, we selected a Pt-coated AFM tip in measurement because the work functions of ZnO and Pt are approximately the same (5.3eV). The samples were adhered to the sample stage by conducting glue. The Pt-coated conducting tip was placed on the top surface of an individual ZnO micro-prism and served as cathode and anode under the forward and reverse bias, respectively. Figure 3(a) shows the Schematic illustration of the *I–V* measurement by AFM. Both of the samples are subject to a forward bias (0–5V) and a reverse bias (0–−5V). The *I–V* curves of the interface junction are depicted in Fig.3(b). It is clearly seen that the interface junction between the p-type Si substrate and the ZOMP obviously exhibits the *I-V* curve being nonlinear and rectifying behaviour, while the interface junction between the n-type Si substrate and the ZOMP displays the *I–V* curve of the ohmic contact being linear. The *I–V* characteristic curve of the p–n interface junction shows a turning point at a voltage of about 1V for the forward bias and a breaking point at a voltage of −4.9V for the reverse bias. From the *I–V* curves, one can find that the interface junctions act as p–n and ohmic junctions for the ZOMPs with the p-type substrate and the n-type substrate respectively. The p–n and ohmic junctions are presumably formed due to the intrinsic defects (oxygen vacancies and Zn interstitial atom)[13] appearing in ZnO material which can turn the ZOMP into natural n-type conduction.

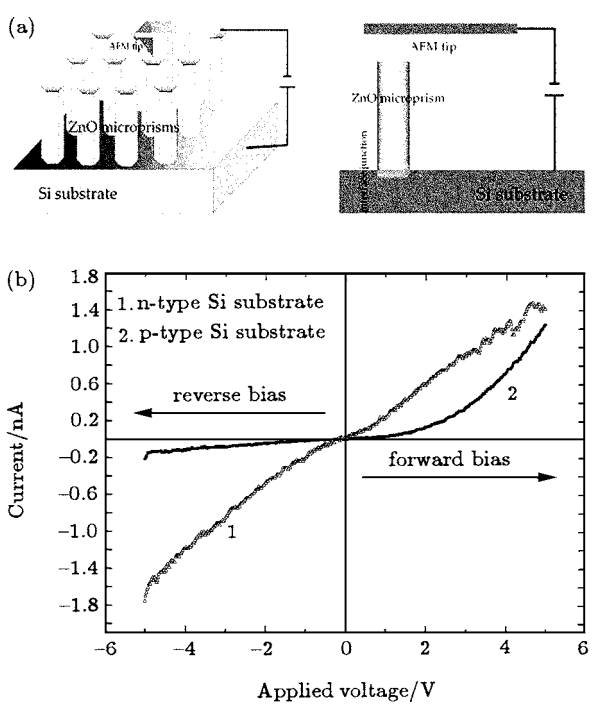



**Fig.3.** (a) Schematic illustration of the *I–V* measurement by AFM and (b) *I-V* curves of the interface junction between individual ZnO micro-prism, separately, with a p-type and an n-type Si substrate.

To avoid the uncertainty and the screen effect[14] of field emission from such a bushy forest of emitters, we studied the field emission from a single ZOMP by using AFM. In this measurement, the Pt-coated conducting tip acting as an anode was hoisted up 10$\mu$m above the top surface of an individual ZnO microprism acting as a cathode (Fig.4(a) shows the diagrammatic sketch). The working pressure was $10^{-7}$

Torr without baking the samples. The relationship between the field emission current $I_{\text{emiss}}$ and the applied voltage $V_{\text{appl}}$ is shown in Fig.4(b). In Region (i), the weak current just emerge from the background noise. The fluctuation of the current in Region (ii) is evidence of degasification. Both degasification and electron emission coexist in Region (iii), i.e. the transition region. The real electron emission behaviour takes place when the applied voltage is increased to 3.4V as indicated in Region (iv). The onset voltage (defined as the voltage at which $I_{\text{emiss}}$ can be just distinguished from the background noise) of the emitter based on the n-Si/n-ZnO ohmic interface junction is 1.5V that is 0.5V lower than based on the p-Si/n-ZnO interface junction. In addition, the emission current from the ZOMP based on the n-Si/n-ZnO ohmic interface junction is higher than based on the p-Si/n-ZnO interface junction as shown in Region (iv). Even though the applied voltage is increased to 4.9V (reverse breakdown voltage), no jump of emission current is found for the p–n interface junction based on ZnO micro-prism. The possible reason is that the potential is shared by the space charge layer of the p–n interface junction and work distance between AFM tip and ZOMP.

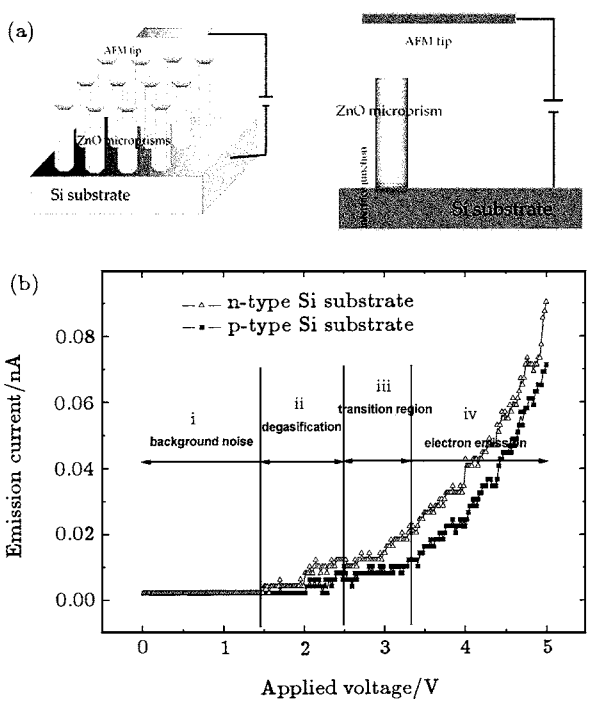



**Fig.4.** (a) Schematic illustration of field emission measurement by using AFM. (b) Field emission $I_{\text{emiss}}$–$V_{\text{appl}}$ curves from the individual ZnO microprism grown, separately, on a p-type substrate and an n-type Si substrate.

The relationship between the emission current and the applied voltage can be analysed using the Fowler–Nordheim equation,[15] i.e. plotting $\ln(I_{\text{emiss}}/V_{\text{appl}}^2)$ versus $1/V_{\text{appl}}$. Figure 5 shows the F-N plots obtained from the measured $I_{\text{emiss}}$–$V_{\text{appl}}$ curves, which clearly indicate that the behaviours of the samples vary with applied voltage increasing and may be sequentially described in the following four phases: (i) background noise, (ii) degasification, (iii) transition process, and (iv) actual emission as indicated in Fig.5. It can be seen that the curves in the emission phase (iv) are consistent with the F-N tunnelling mechanism by exhibiting a roughly linear dependence; accordingly, the electron emission exhibits the behaviour of tunnelling through the surface barrier. The intense fluctuations of the data in the phases (ii) and (iii) presumably were derived from the following facts: (a) the ZnO microstructure was not heat-treated for desorbing the gas; (b) the emission current from an individual ZOMP was too small to be monitored accurately.

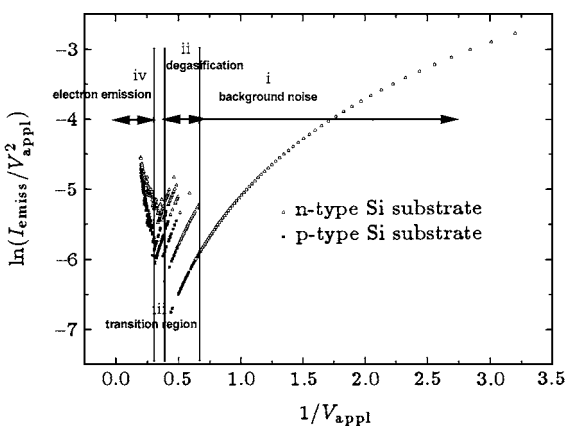



**Fig.5.** F-N plots obtained from the $I_{\text{emiss}}$–$V_{\text{appl}}$ curves. The different regions of the curves exhibit different behaviours as indicated.

The better electron emission properties of the ZOMP on n-type Si substrate may be ascribed to the contribution of the n-Si/n-ZnO ohmic contact. For the ZOMP grown on the p-type Si substrate, the interface junction serves as a p–n junction owing to the intrinsic n-type conduction of ZnO material. When measuring the emission current, a reverse bias is applied to the p-Si/n-ZnO interface junction. As a result, the rectifying behaviour restricts the electron injection into the ZOMP, i.e. the electron density of ZOMP based on the p-type Si substrate is less than on the n-type Si substrate. Grounding on the tunnelling mechanism, the quantity of emission electrons is expressed

as $N_{\text{emission}} = T \times N_0$. (The tunnelling coefficient $T$ is fixed by the electron energy and the height and width of the barrier.) So the emission current is limited by the rectifying behaviour of the p-Si/n-ZnO interface junction.

As far as the interface junctions are concerned, both of them are heterojunctions (n-Si/n-ZnO, p-Si/n-ZnO). The schematic diagrams of energy band are shown in Fig.6. Due to the discrepancy between band-gaps of Si(1.12eV) and ZnO(3.37eV), there exist discontinuities: $\Delta E_{\text{c}}$ in conduct band and $\Delta E_{\text{V}}$ in valence band (where $\Delta E_{\text{c}} + \Delta E_{\text{V}} = E_{\text{g,ZnO}} - E_{\text{g,Si}}$).

For the n-Si/n-ZnO heterojunction shown in Fig.6(a), the peak $\Delta E_{\text{c}}$ is smaller than the gap $\Delta E_{\text{V}}$. If the ZnO micro-prisms were doped moderately, the barrier peak $\Delta E_{\text{c}}$ would be low enough and the depletion layer would be thin enough for electron tunnelling, so the transportation characterization would be of ohmic contact. The big gap $\Delta E_{\text{V}}$ in valence band would not affect the transportation characterization notably because the hole is in minority on this occasion. When a reverse bias was applied, there was no obvious change in $\Delta E_{\text{c}}$ and $\Delta E_{\text{V}}$, so the n-Si/n-ZnO heterojunction here acts as a fixed ohmic resistor and its $I$–$V$ curve is consistent with that of our experiment (Fig.3(b)).

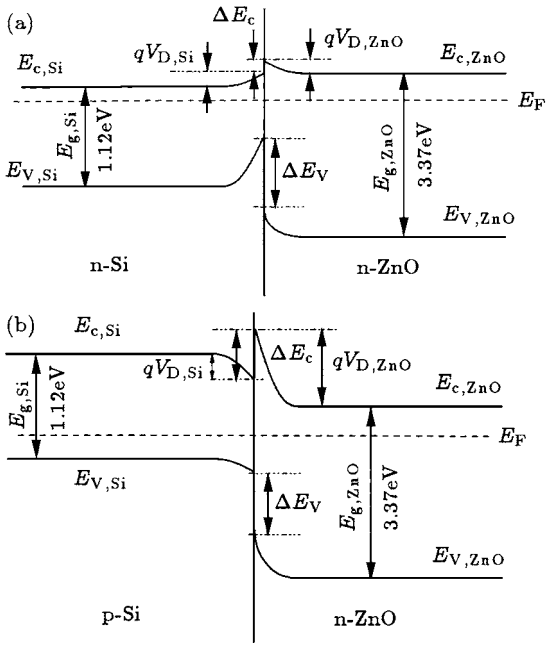



**Fig.6.** The schematic diagrams of energy band for n-Si/n-ZnO heterojunction (a) and p-Si/n-ZnO heterojunction (b).

For the p-Si/n-ZnO heterojunction shown in Fig.6(b), the current density is

$$J = J_{\text{n}} + J_{\text{p}} = q\left(\frac{D_{\text{n,Si}}}{L_{\text{n,Si}}} n_{\text{Si}} + \frac{D_{\text{p,ZnO}}}{L_{\text{p,ZnO}}} p_{\text{ZnO}}\right)\left[\exp\left(\frac{qV}{k_0 T}\right) - 1\right]. \tag{1}$$

Here, $D$ and $L$ are diffusion coefficient and diffusion length, n and p are the electron density and the hole density, $V$ is the voltage on the heterojunction, $k_0$ is Boltzmann constant. From this equation, we find that the relationship between current density $J$ and voltage $V$ follows the Shockley equation[16] like the p–n homojunction, which is confirmed by experiment in Fig.3(b). However, the transportation characterization of the heterojunction is more complex than that of homojunction. Equations (2) and (3) describe in detail the electron current density and the hole current density, respectively:

$$J_{\text{n}} = \frac{qD_{\text{n,Si}} n_{\text{ZnO}}}{L_{\text{n,Si}}} \exp\left[\frac{-q\left(V_{\text{D}} - \Delta E_{\text{c}}\right)}{k_0 T}\right] \exp\left(\frac{qV}{k_0 T} - 1\right), \tag{2}$$

$$J_{\text{p}} = \frac{qD_{\text{p,ZnO}} n_{\text{Si}}}{L_{\text{p,Si}}} \exp\left[\frac{-q\left(V_{\text{D}} + \Delta E_{\text{V}}\right)}{k_0 T}\right] \exp\left(\frac{qV}{k_0 T} - 1\right). \tag{3}$$

In this case, the heterojunction consists of p-type Si (narrow band-gap) and n-type ZnO (wide band-gap), so the $\Delta E_{\text{c}}$ and $\Delta E_{\text{V}}$ are both positive. Thus, the barrier height for electrons decreases from $qV_{\text{D}}$ to $qV_{\text{D}} - \Delta E_{\text{c}}$, while the barrier height for holes rises from $qV_{\text{D}}$ to $qV_{\text{D}} + \Delta E_{\text{V}}$. When the field emission performance is measured, a reverse bias is applied to this heterojunction, the barrier heights for both electrons and holes are raised, accordingly, the emission current is limited, which is different from the transportation

of n-Si/n-ZnO heterojunction.

## 3. Conclusion

ZnO micro-prisms are prepared on the p-type and n-type Si substrates, separately. The $I$–$V$ curves of the samples indicate that the interface junctions between substrate and root of micro-prism act as p–n junction and n–n junction because of the intrinsic n-type conduction of ZnO. Field emission measurements show that the individual ZOMP grown on an n-type Si substrate exhibits better electron emission performance than on a p-type substrate. In view of this, we deem that the n-Si/n-ZnO interfacial ohmic contact makes a contribution to the electron emission; however, the p-Si/n-ZnO interface junction deteriorates the electron emission. This study opens up possibilities for using ZnO as the cathode material in field emission devices just by selecting appropriate materials as its substrates.

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