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## Research Article

## Multifunctional Ir–Ru alloy catalysts for reversal-tolerant anodes of polymer electrolyte membrane fuel cells

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## ABSTRACT

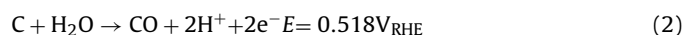
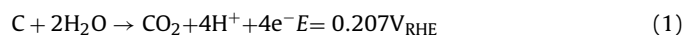
To address the problem of fuel starvation in fuel-cell electric vehicles, which causes cell voltage reversal and results in cell failure when repeated continuously, we developed a reversal-tolerant anode (RTA) to promote water oxidation in preference to carbon corrosion. Graphitized carbon-supported Ir–Ru alloys with different compositions are employed as RTA catalysts in an acidic polyol solution and are shown to exhibit composition-dependent average crystallite sizes of < 5.33 nm. The adopted approach allows the generation of relatively well-dispersed Ir–Ru alloy nanoparticles on the carbon support without severe agglomeration. The activity of IrRu<sub>2</sub>/C for the hydrogen oxidation reaction is 1.10 times that of the state-of-the-art Pt/C catalyst. Cell reversal testing by simulation of fuel starvation reveals that the durability of IrRu<sub>2</sub>/C (~7 h) significantly exceeds that of the conventional Pt/C catalyst (~10 min) and is the highest value reported so far. Thus, the developed Ir–Ru alloy catalyst can be used to fabricate practical RTAs and replace Pt catalysts in the anodes of polymer electrolyte membrane fuel cells.

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## 1. Introduction

The energy efficiency of fuel-cell electric vehicles (FCEVs) is much higher than that of vehicles with internal combustion engines. Polymer electrolyte membrane fuel cells (PEMFCs) are used to supply power for FCEVs employ hydrogen and oxygen as fuel, and discharge water as the only product, thus featuring the advantage of zero greenhouse gas emission [1–3]. However, the widespread commercialization of FCEVs is hindered by the high cost, suboptimal performance, and low durability of the corresponding cells. In this regard, both industry and academia have highlighted that PEMFC components and systems need to be highly durable and robust under various operating conditions. One of the major reasons for poor membrane electrode assembly (MEA) performance in FCEVs is deterioration caused by hydrogen fuel starvation due to harsh operating conditions such as water flooding, freezing, and sudden acceleration. When there is sufficient stoichiometric supply of hydrogen fuel and oxygen (air) to the anode and cathode, respectively, fuel cell operation normally involves a

hydrogen oxidation reaction (HOR) at the anode and oxygen reduction reaction (ORR) at the cathode. However, under conditions of hydrogen shortage, the anode potential increases more than the cathode potential, eventually causing cell voltage reversal. Upon cell reversal (CR), the high voltage (i.e., > 1 V) at the anode accelerates the carbon oxidation reaction (COR, Eqs. (1) and (2)) and the oxygen evolution reaction (OER, Eq. (3)) at the anode [4]:



From a kinetic perspective, the OER is generally more favorable than the COR and thus proceeds faster, even though the COR is thermodynamically favorable. When the anode potential increases to > 1 V because of CR, the COR is accelerated, causing degradation of the carbon supports in the anode [5]. Considering the high frequency of fuel starvation occurrence, the continued corrosion of carbon supports may cause the dissolution and agglomeration of Pt catalyst particles, ultimately decreasing the electrochemical surface area (ECSA) of the catalyst [6]. In addition, repeated corrosion of the carbon support makes the catalyst layer thinner and increases its contact resistance and hydrophilicity, elevating mass transfer resistance [7,8]. Furthermore, high-frequency resis-

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