Syntheses and activities of indol-2-ylidene-ligated ruthenium-based olefin metathesis catalysts

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Here we report a new family of indol-2-ylidene (IdY)-ligated Ru-based olefin metathesis catalysts (Ru–IdY) and their X-ray crystal structures which show a unique conformation of the ruthenium environment. Catalytic activities of Ru–IdY catalysts were investigated for ring-closing metathesis, ring-opening metathesis polymerization, and ethenolysis, which show excellent turnover numbers (TONs).

Olefin metathesis is one of the most important catalytic reactions for the formation of new C=C bonds.[1] Over the past three decades, olefin metathesis polymerization,[2] macrocyclization,[3] and ethenolysis[4] reactions have been developed in industry and academia. Ru-based olefin metathesis catalysts are well-defined molecular systems and exhibit significant reactivities.[5] Particularly, second-generation Ru-based catalysts bearing N-heterocyclic carbenes (NHCs, **HG2**) instead of phosphine ligands (**HG1**) have been widely studied because of their high reactivities and stabilities.[6] The high reactivities and stabilities of these catalysts mainly originate from the strong σ-donating properties of NHC ligands, which strengthen the bonds between the carbenes of NHC ligands and Ru and enhance the affinity of Ru for π-acidic olefins.
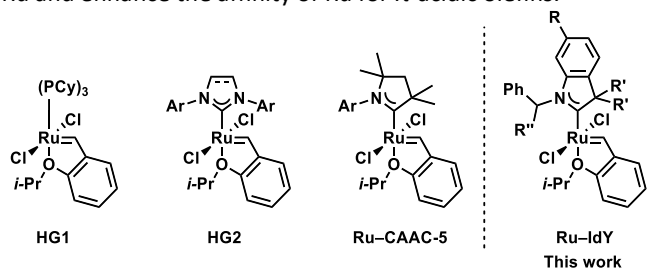

Figure 1. Representative Ru catalysts with various ligands.

Recently, a new family of Ru-based olefin metathesis catalysts, **Ru–CAAC-5**, has been developed by introducing additional σ-donating and π-accepting (ambiphilic) cyclic (alkyl)(amino) carbene (CAAC) ligands into Ru-based catalysts.[7] The performances of **Ru–CAAC-5** have surpassed those of the second-generation Ru-based catalysts, specifically for macrocyclization[7b, 7d] and ethenolysis[7b, 7d, 8]. The strong ambiphilic character of CAAC ligand plays a major role in the outstanding catalytic performances and stabilities of **Ru–CAAC-5** against β-hydride elimination decomposition.[9]

Installing ambiphilic carbene ligands to Ru-based olefin metathesis catalysts enhanced catalytic activities as compared to those of Ru-based metathesis catalysts.[7a] However, owing to its strong ambiphilicity, carbene has low stability, making the preparation of ambiphilic carbene-based metal complexes difficult.[10] Consequently, very few studies have been reported on the syntheses of Ru-based olefin metathesis catalysts bearing ambiphilic carbene ligands. For example, in 2015, Bertrand and Grubbs developed the best performing catalyst **Ru–CAAC-5** for the ethenolysis of methyl oleate (TON: 180000 at 3 ppm).[8] In 2019, Hong et al. reported an efficient ethenolysis catalyst (TON: 100000) using asymmetric abnormal NHCs with ambiphilic characters.[11] In 2020, Grubbs et al. also fabricated an ethenolysis catalyst bearing a six-membered CAAC ligand (**Ru–CAAC-6**); nevertheless, it was less efficient for ethenolysis (TON: 1720).[12] In 2022, Hong et al. reported a highly selective ethenolysis catalyst containing acyclic aminooxycarbenes (TON: 100000, selectivity: 97%).[13]

Recently, our group developed a new type of CAAC ligand, indol-2-ylidene (IdY), that has strong ambiphilicity and tunable electronic and steric properties.[14] Thus, it is reasonable to hypothesize that robust and efficient olefin metathesis catalysts can be generated using IdY ligands because the ambiphilic character of carbene strengthens the carbene–metal bonds and increases the stability of the catalyst against β-hydride elimination decomposition.[9] Furthermore, due to the tunable electronic and steric properties of IdY ligands, various olefin metathesis catalysts with different electronic or steric characteristics can be synthesized using these ligands.

Herein, we report a series of IdY-ligated Ru-based (**Ru–IdY**) olefin metathesis catalysts. Their unique structures were characterized by X-ray crystallography, which revealed the unique conformations of **Ru–IdY** catalysts as compared to those of other known **Ru-CAAC** type olefin metathesis catalysts. Moreover, the performances of **Ru–IdY** catalysts were examined for ring-closing metathesis (RCM), ring-opening metathesis polymerization (ROMP), and ethenolysis.
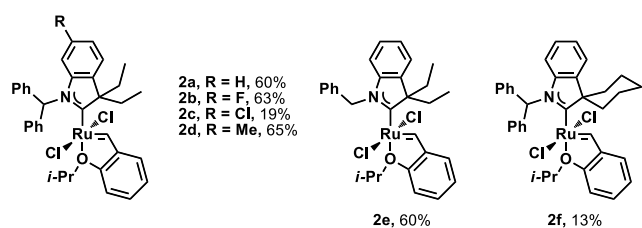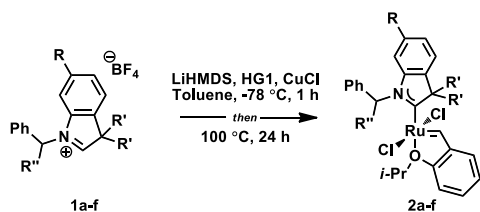
Scheme 1. Synthesis of **Ru–IdY** catalysts (**2a–f**).

Initially, six IdY precursors (**1a–f**) were prepared in two steps by a previously reported method.[14a] H, F, Cl, and CH_3 groups were separately introduced into the aryl backbone of **1** to alter the electronic properties of carbene carbon (**1a, b, c,** and **d,** respectively). To reduce the steric effect on N, we inserted a benzyl group (**1e**) instead of a benzhydryl group into **1a**, and a cyclohexyl group (**1f**) was also used to control the steric environment of the quaternary carbon (for details, see the Supporting Information (SI)). **1a** was used for optimizing the synthesis of **2a** (**Table S1**). Tetrahydrofuran (THF) solvent was used at room temperature as the original condition for inserting **1a** into **HG1**; however, the desired product was not obtained, as indicated by the absence of a highly deshielded proton peak of the product in the corresponding proton nuclear magnetic resonance (¹H NMR) spectrum. When toluene as solvent was employed instead of THF at room temperature, the characteristic peak of the desired product was detected at 18.7 ppm; nevertheless, the desired product was acquired in trace amount. When the temperature was increased to 100 °C, **2a** was achieved in 60% yield, and six different catalysts, **2a–f**, were successfully synthesized under this condition (**Scheme 1**).

A set of degradation tests was conducted to investigate the stabilities of the catalysts. Solutions containing **2a–f** (0.01 M) and 1, 3, 5-trimethoxybenzene as an internal standard in deuterated benzene (C_6D_6) were prepared and heated for 3 weeks at 40 °C. Decomposition ratios of the catalysts were determined by integrating the peaks of the benzylidene protons of **2a–f** and the methoxy groups of 1, 3, 5-trimethoxybenzene (**Figure S1**). Interestingly, the integration ratio of the peaks of the benzylidene proton and the methoxy group was retained (degradation was within 10%) for 3 weeks, except for the case of **2f**. Only 2% of **2a** (the most stable complex) decomposed

after being stored in a C_6D_6 solution for 3 weeks at 40 °C. Nevertheless, only 67.8% **2f**, which had the highest sterically demanding environment, was retained after storage in a C_6D_6 solution for 3 weeks at 40 °C.
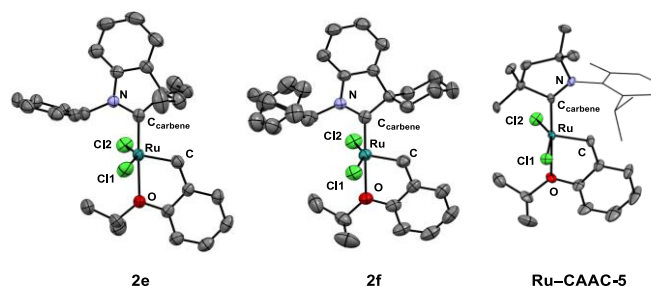

Figure 2. Solid-state structures of **2e**, **2f**, and **Ru−CAAC-5**[8] with thermal ellipsoids drawn at 50% probability. For clarity, H atoms and solvent molecules have been omitted.

Single crystals of **2e** and **2f** were obtained and clearly characterized via X-ray diffraction (**Figure 2**). The $C_{carbene}−Ru−O$ angles are 177.58 ° (**2e**) and 176.82 ° (**2f**). The $C_{carbene}−Ru$ bonds in **2e** and **2f** (1.929(7) and 1.936(0) Å, respectively) are shorter than those in **SIMes−Ru** (1.981 Å),[6] **Ru−CAAC-5** (~1.95 Å),[8] and **Ru−CAAC-6** (~1.96 Å)[12] because of the ambiphilicity of IdY. The ambiphilicity of IdY was also proved by the longer Ru−O bonds in **2e** and **2f** (2.313(1) and 2.286(9) Å, respectively) than that in **SIMes−Ru** (2.261 Å).[6] However, these bonds are significantly shorter than those in **Ru−CAAC-5** (~2.33 Å)[8] and **Ru−CAAC-6** (~2.37 Å)[12] This disagreement can be explained based on the steric effect, which is affected by less sterically hindered N-benzyl or N-benzhydryl groups. The low % buried volumes (%V_{bur}) of **2e** and **2f** (55.6 and 55.9%, respectively) as compared to those of **Ru−CAAC-5** (~62.6%)[8, 15] and **Ru−CAAC-6** (~62.2%)[12] indicate steric effects (see SI).

Interestingly, IdY exhibited the same conformation as the benzylidene group in all X-ray crystal structures. Unlike the case of **Ru−CAAC**,[8, 15] the quaternary carbon is positioned above the benzylidene scaffold, and the N-alkyl group is located over an empty coordination site in **Ru–IdY**. Although negative steric interactions occur between the ethyl or cyclohexyl groups on the quaternary carbon and the benzylidene proton, steric hindrance between the proton of the N-alkyl group and benzylidene proton plays a crucial role in the exceptional conformation of **Ru–IdY**. Furthermore, even after **IdY–Ru** bond was rotated by 180° intentionally for density functional theory (DFT) optimization, the angle between the IdY plane and the Ru−benzylidene plane returned to 47.8 ° (see SI). This conformation decreased the interaction between the d-orbitals of Ru and the empty p-orbital of the $C_{carbene}$ of IdY, which contributed to the reduction of the bond distance between $C_{carbene}$ (**IdY**) and Ru (1.974 Å from 1.965 Å).
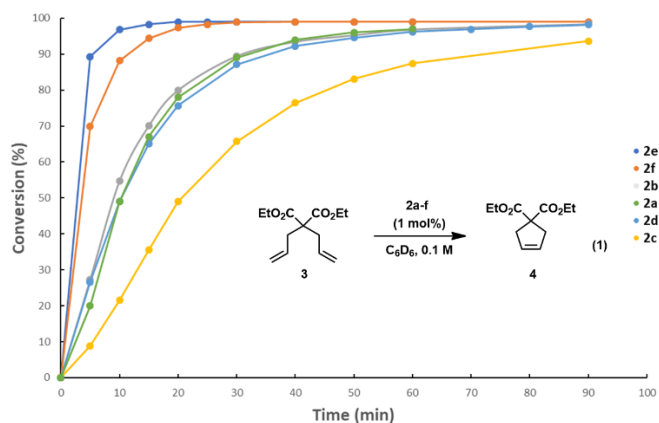
Figure 3. Ring-closing metathesis (RCM) of diethyl diallylmalonate (**3**) using **2a**–**f**.

RCM of diethyl diallylmalonate (**3**) was performed using 1 mol% **2a**–**f** in benzene (0.1 M) at 30 °C (Equation 1). After 90 min, full conversion was achieved in all the cases, except for **2c** (**Figure 3**). In the cases of **2e** and **2f**, full conversion occurred within 30 min. This implies that the steric environment plays an important role in the RCM reactivities of **2**, whereas electronic variation is not a crucial factor compared with steric variation (**2a**, **2b**, and **2d**). Nevertheless, for **2c** bearing electronically deficient IdY, 90% conversion was obtained in more than an hour. This result demonstrates that high σ-donating property is still important for the RCM reactivity of **2**.
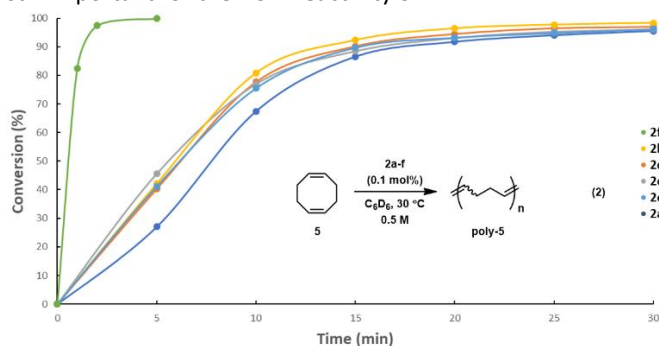

Figure 4. Ring-opening metathesis polymerization (ROMP) of 1, 5-cyclooctadiene (**5**) using **2a**–**f**.

ROMP of 1, 5-cyclooctadiene (**5**) was also conducted using 0.1 mol% **2a**–**f** (Equation 2). Conversion of **5** to the product (**poly-5**) over time is depicted in **Figure 4**. Interestingly, **2f** led to almost full conversion of **5** within 2 min; nevertheless, in other cases, nearly complete conversion of **5** was observed in 30 min. These results are similar to those obtained for the RCM, which is more affected by the steric environment than by the electronic characteristics of **2**.
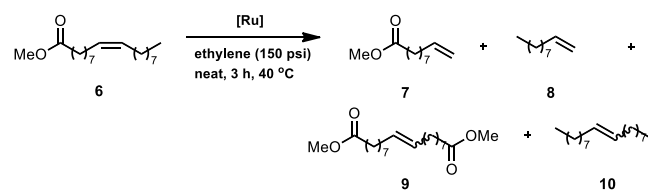
[Ru] (ppm)	Sel (%)[a]	Con (%)[b]	Yield (%)[c]	TON[d]
2a (50)	88	89	79	15700
2a (10)	94	46	44	44800
2a (5)	96	21	20	40900
2e (50)	91	91	84	16800
2e (10)	91	46	42	42600
2e (5)	92	32	30	59633
2e (4)	94	23	22	56400
2e (3)	95	19	18	61200
2f (100)	30	63	19	1900
2f (50)	25	51	13	2600
2f (10)	27	14	4	4100

Table 1. Ethenolysis of methyl oleate (**6**) using **2a**, **2e**, and **2f**. [a]Selectivity, [b]Conversion, [c]GC yield (Tridecane as internal standard), [d]Turnover numbers.

Moreover, ethenolysis of methyl oleate (**6**) was performed using **2a**, **2e**, and **2f** under solvent-free conditions (**Table 1**). In the case of **2a**, a TON of 44800 and a selectivity of 94% were acquired at a catalyst loading of 10 ppm. This result also verifies that **2a** is a more efficient catalyst for ethenolysis than the previously reported NHC-based catalysts (TON: 2000–5000)[16]. However, catalysts with TONs of at least 50000 are recommended for use in the manufacture of commodity chemicals.[17] Satisfactorily, the sterically less hindered catalyst **2e** exhibited a better TON (61200) and selectivity (95%) at a loading of 3 ppm. In contrast, **2f**, which is the most sterically demanding catalyst among **2a**–**2f**, demonstrated less reactivity (TON: 4,100, selectivity: 27%) at a loading of 10 ppm. The inferior performance of **2f** was mainly due to the strong steric effect.[11, 13, 18] Ring flip of the cyclohexyl group effectively covered the Ru center and hindered the facile binding of the substrate to **2f**. This tendency was also discovered in the case of sterically demanding **Ru−CAAC-6**, which exhibited low performance (TON: 1720) as compared to that of less bulky **Ru−CAAC-5** (TON: 24180).[12]
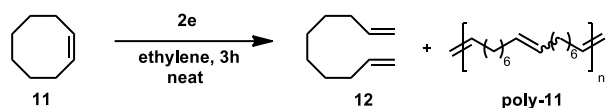
2e (ppm)	Ethylene (psi)	Temp (°C)	Sel (%) [a]	Con (%) [b]	Yield (%) [c]	TON [d]
50	300	40	44	99	44	8700
20	200	40	50	92	46	23200
20	300	40	53	94	50	24200
20	400	40	58	94	55	27200
20	400	r.t.	68	94	64	33000
20	400	30	73	93	67	34000
10	400	30	70	78	54	53200

Table 2. Ethenolysis of *cis*-cyclooctene (**11**) using **2e**. [a]Selectivity, [b]Conversion, [c]GC yield (Tridecane as internal standard), [d]Turnover numbers.

Production of valuable acyclic *α,ω*-dienes by the ethenolysis of cycloalkenes is challenging because of competition between the ROMP and ethenolysis of cycloalkenes. In 2017, Sigman and Togni reported that the electron-accepting property of the NHC ligand plays a major role in the selectivity of the catalyst against ROMP.[19] In 2022, Hong et al. revealed that a highly σ-donating carbene ligand also increased the selectivity of the catalyst against ROMP.[13] These results encouraged us to explore the ethenolysis of *cis*-cyclooctene (**11**) using **Ru−IdY** catalysts. Inspired by the results of the ethenolysis of **6**, we employed **2e** as a catalyst for this reaction. **Table 2** presents the effects of catalyst loading, temperature, and pressure of ethylene gas on the performance of **2e**. With an increase in the ethylene gas pressure, the TON enhanced; furthermore, when the temperature was decreased to 30 °C, the TON and selectivity increased. **2e** demonstrated the best performance (TON: 53200 and selectivity: 70%) at a low loading of 10 ppm. These results strongly support that **2e** are highly useful catalysts for the ethenolysis of cycloalkenes and exhibit better performances than those of NHC-based Ru catalysts (TON: up to 2300 and selectivity: up to 68%).[19]

In conclusion, herein, a series of Ru-based olefin metathesis catalysts bearing ambiphilic **IdY** was developed. Moreover, six different **Ru−IdY** olefin metathesis catalysts were prepared and comprehensively characterized. Via X-ray diffraction, the unique conformations of these catalysts were confirmed for the first time in this study. These conformations should provide a valuable understanding of the activities of **Ru−CAAC** type catalysts. Catalytic activities of **Ru−IdY** catalysts for RCM, ROMP, and ethenolysis were examined. These catalysts demonstrated high performances for the ethenolysis of methyl oleate and *cis*-cyclooctene (TON: 61200 and selectivity: 95% for methyl oleate and TON:53200 and selectivity: 70% for *cis*-cyclooctene).

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