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# Bimetallic Oriented ( $\overline{\text{Au}}/\overline{\text{Cu}}_2\text{O}$ ) versus monometallic 1.1.1 $\overline{\text{Au}}$ (0) or 2.0.0 $\overline{\text{Cu}}_2\text{O}$ Graphene supported Nano-platelets as very efficient Catalysts for Michael and Henry Additions

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**Abstract:** Michael and Henry addition reactions have been investigated using mono ( $\overline{\text{Au}}$  and  $\overline{\text{Cu}}_2\text{O}/\text{f-G}$ ) and bimetallic nanoplatelets ( $\overline{\text{Au}}/\overline{\text{Cu}}_2\text{O}/\text{f-G}$ ) grafted onto few-layers graphene (f-G) films as heterogeneous catalysts by comparison with homogeneous NaOH and  $\text{K}_2\text{CO}_3$  ones. In the presence of the heterogeneous catalysts these reactions occurred in the absence of any extrinsic (NaOH and  $\text{K}_2\text{CO}_3$ ) base with turnover numbers (TONs) at least four orders of magnitude higher. While the homogeneous catalysts provided TONs close to the unity for  $\overline{\text{Au}}/\overline{\text{Cu}}_2\text{O}/\text{f-G}$  this was of the order of  $10^7$ . These reactions also occurred with a very good selectivity to the targeted products. These performances are in line with the basicity of these catalysts demonstrated from  $\text{CO}_2$  chemisorption measurements. The effect of the nano-size and the interaction of the nano-particles with the graphene are also important to achieve this high activity.

## Introduction

Michael addition, as originally defined, [1], is the addition of an enolate of a ketone or aldehyde or a doubly stabilized carbon nucleophile [2] to an  $\alpha,\beta$ -unsaturated carbonyl compound at the  $\beta$

carbon. Thus, this reaction consists on the nucleophilic 1,4-addition of a carbanion or another nucleophile to an  $\alpha,\beta$ -unsaturated carbonyl compound [3]. This reaction is catalyzed by both acid [4] and base [5] catalysts. More recently, the homogeneous catalysts utilized in this reaction were enlarged by using metal complexes [6] and organocatalysts [7]. Organic superbase, 1,1,3,3-tetramethylguanidine functionalized graphene oxide has also reported to promote the Michael addition of malonates [8]. The use of metal complexes and organocatalysts has allowed expanding the scope of this reaction for the synthesis of complex molecules [9].

Besides these, heterogeneous catalysts exhibiting acid and base properties have also been investigated in this reaction [10]. In this context, among many other types of heterogeneous catalysts, the last two decades have seen an impressive number of examples showing the activity, and especially the selectivity of gold and copper in many catalytic reactions. For the particular case of the Michael addition the reported studies indicated that the selectivity can be controlled by tuning the oxidation state of Au from 0 to (I) and (III) [11]. Au support, consisting of an organic functionalized material or an oxide, should play the role controlling the charge density on the Au nanoparticles [12]. Au nanoparticles may exhibit an even more complex behavior. They can generate and stabilize electron-rich carbenes on their surface, after an electronic transfer to the anti-bonding valence orbitals of the C-O group of substrates [13]. Thus, beyond gold-catalyzed Michael additions, this constitutes an example of how gold nanoparticles modify the electronic density of unsaturated bonds [14]. The interaction of copper with organic functionalities of a support [15] or with the support itself [16] is producing quite similar effects in this reaction.

Besides Michael addition, the Henry reaction is other classic carbon-carbon bond formation reaction, consisting in the addition of a nucleophilic anion derived from nitroalkane to an electrophilic aldehyde or ketone [17]. Typically, it utilizes only a

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catalytic amount of a homogeneous catalyst that could be alkali metal hydroxides, alkoxides, carbonates, triflates, compounds of fluoride anion or nonionic organic amines [18]. Other homogeneous catalysts utilized in this reaction are metal complexes [19]. Base-heterogeneous catalysts as Mg-Al hydrotalcite have been used as well [20].

Beside catalytic activity, the use of Cu-complexes bearing various ligands has allowed also to gain dia- and stereoselectivity in the Henry reaction [21].

However, the literature referring to heterogeneous catalysts with Cu for the Michael reaction is scarce and refers either to immobilized Cu(II) complexes [22] or to MOF systems incorporating Cu [23]. For Au as catalyst, in our best knowledge there is no other precedent in this reaction.

Graphene, an allotrope of carbon, has been considered as an excellent suitable catalytic support due to its high carrier mobility, high electrical and thermal conductivity, high surface area (theoretical value of 2630 m<sup>2</sup>/g), unique two-dimensional (2D) honeycomb lattice, high electron mobility, strong metal-support interactions and easy surface functionalization [24-25]. In addition, doping graphene-nanosheets with heteroatoms became an attractive method of tuning its electronic and catalytic properties [26].

On the other side, graphene supported metal nanoparticles (MNPs) have already shown very active and selective properties for various organic transformations such as: oxidations [27], reductions [28-29] or coupling reactions [30-32]. In this context, we recently demonstrated that coupling reactions can be efficiently catalyzed by MNPs strongly grafted on few- and multilayer defective graphenes prepared by pyrolysis of natural polysaccharides containing metal salts (ie. AuCl<sub>4</sub><sup>-</sup> or Cu<sup>2+</sup> as source of metal ions) [33]. Furthermore, the pyrolysis of thin films of alginate can provide *fl-G* (*fl* meaning few layers structures; *G* meaning defective graphene) of few nanometers thickness [34-35]. Under pyrolysis at 900°C in inert atmosphere copper is orientated onto the graphene as (1.1.1)  $\overline{Cu}/fl-G$  which after exposure to air spontaneously render to oriented (2.0.0) copper (I) oxide nanoplatelets ( $\overline{Cu}_2O/fl-G$ ). Under the same conditions, onto the few layers of graphene, Au<sup>3+</sup> generates (1.1.1) oriented Au nanoplatelets ( $\overline{Au}/fl-G$ ), where the lateral sides correspond to (0.0.1) oriented planes [9].

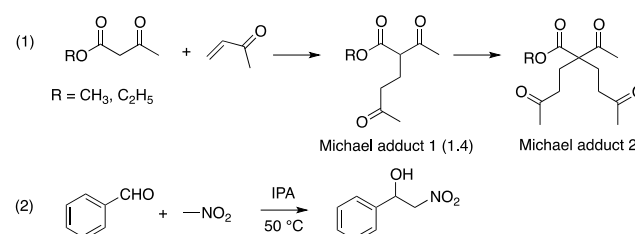
In order to prove the versatility of the graphene supported MNPs in coupling reactions in this study we extended the investigation of these materials from the monometallic to bimetallic  $\overline{Au}/\overline{Cu}_2O/fl-G$

films looking for a synergistic effect in two important C-C coupling reactions, namely Michael and Henry additions [36]. Henry reaction is a "nitroaldol condensation" and one of the most atom-economical C-C coupling processes [37-38]. Under classical conditions, both reactions require basic or acidic catalysts in the presence of organic solvents, and long reaction times, which may lead to environmentally hazardous residues and undesirable by-products [39-43].

## Results and Discussion

Monometallic  $\overline{Cu}_2O/fl-G$  and  $\overline{Au}/fl-G$  catalysts were exhaustively characterized as described in our previous works [31, 33]. Briefly, in accordance to TEM images combined with the analysis of the diffraction patterns of back scattered electrons, the oriented  $\overline{Cu}_2O/fl-G$  are constituted from Cu<sub>2</sub>O nano-platelets which exhibit a preferential (2.0.0) facet orientation [33] while  $\overline{Au}/fl-G$  catalysts display a preferential (1.1.1) facet orientation irrespective the Au loading and the thickness of G [31]. To illustrate the  $\overline{Au}/fl-G$  materials used as catalysts in the present study that are coincident with those previously reported, [31] supplementary material presents a transmission electron microscopy image of the  $\overline{Au}/fl-G$  sample.

Catalytic performance of these oriented nanoplatelets on graphene were checked in two reactions controlled by completely different mechanisms, such as Michael (Scheme 1, Eq. 1) or Henry additions (Scheme 1, Eq. 2). For the Michael addition, the experiments were carried out considering methyl acetoacetate (MeAcOAc) and ethyl acetoacetate (EtAcOAc) as activated methylene substrates and methyl vinyl ketone (MVK) as Michael acceptor. The considered Henry addition is the coupling of benzaldehyde with nitromethane to nitroaldol. Michael addition was investigated in water, while the Henry addition in both protic (isopropyl alcohol, IPA) and aprotic solvents (heptane).



**Scheme 1.** Michael addition of acetoacetates with MVK (1) and Henry reaction of benzaldehyde with nitromethane (2).

Comparative behavior of  $\overline{Au}/fl-G$ ,  $\overline{Cu}_2O/fl-G$  and  $\overline{Au}/\overline{Cu}_2O/fl-G$  films as catalysts in Michael addition

Table 1 compiles results in the presence of  $\overline{Cu}_2O/fl-G$ ,  $\overline{Au}/fl-G$  and  $\overline{Au}/\overline{Cu}_2O/fl-G$  catalysts. With acetoacetates as Michael donors the reaction may proceed in two steps (Scheme 1, Table 1), where the first step leads to the formation of mono adduct MA1 which can be subsequently deprotonated affording the addition of another MVK molecule with the formation, in the second step, of the MA2 product. The catalytic results show that the performances in this reaction are controlled by the nature of the catalyst and of the Michael donor. Prior controls using *fl-G* as catalyst showed the failure of this material to promote either the Michael or the Henry reaction. These preliminary blank controls clearly established that the presence of metal nanoparticles is required to obtain catalytically active materials.

Working with MeAcOAc the homogeneous NaOH base catalyst (Table 1, entry 1) provides a very high conversion but with a relatively low selectivity to MA1 (~12.7%). In the absence of base, on  $\overline{Au}/fl-G$  and  $\overline{Cu}_2O/fl-G$  films (entries 2 and 3) the conversion is lower compared to the homogeneous catalyst, but the achieved selectivity in MA1 is very high. Under the same conditions, bimetallic  $\overline{Au}/\overline{Cu}_2O/fl-G$  films (entry 4) as catalyst, led to a high conversion comparable with that produced by the monometallic  $\overline{Au}/fl-G$ ,  $\overline{Cu}_2O/fl-G$  but with a much higher selectivity in MA1 compared to all the individual catalysts.

Replacing the Michael donor with ethyl acetoacetate (EtAcOAc), led to an increase of the conversion for all the catalysts. Under these conditions the differences between the homogeneous catalyst (NaOH) and the heterogeneous graphenes are very small.

**Table 1.** Catalytic performances of  $\overline{Au}/fl-G$ ,  $\overline{Cu}_2O/fl-G$  and  $\overline{Au}/\overline{Cu}_2O/fl-G$  films in the Michael addition of acetoacetates donors with MVK acceptor

Nr. crt	Michael donor	Base	Graphene Catalyst	Conversion (%)	Selectivity MA1, (%)	Selectivity MA2, (%)
1	MeAcOAc	NaOH	no	100	12.7	87.3
2	MeAcOAc	no	$\overline{Au}/fl-G$	32.4	75.7	24.3
3	MeAcOAc	no	$\overline{Cu}_2O/fl-G$	31.1	77.4	22.6
4	MeAcOAc	no	$\overline{Au}/\overline{Cu}_2O/fl-G$	85.8	72.8	27.2
5	MeAcOAc	no	$Au(0.52wt\%)/fl-G$	5.8	100.0	0
6	EtAcOAc	NaOH	no	100	10.2	89.8
7	EtAcOAc	no	$\overline{Au}/fl-G$	97.0	45.7	54.3
8	EtAcOAc	no	$\overline{Cu}_2O/fl-G$	92.3	63.1	36.9
9	EtAcOAc	no	$\overline{Au}/\overline{Cu}_2O/fl-G$	98.8	100	0
10	EtAcOAc	no	<i>fl-G</i>	0	0	0

Reaction conditions: Michael donor: 1 mmol; Michael acceptor: 1.5 mmoles, Catalyst: 0.12 mmoles NaOH or 1 piece of  $1 \times 1 \text{ cm}^2$  of  $\overline{Cu}_2O/fl-G$  on quartz (0.20 mg of Cu total), or one piece of  $1 \times 1 \text{ cm}^2$  plate of  $\overline{Au}/fl-G$  film (0.24 mg

of Au total) or one piece of  $1 \times 1 \text{ cm}^2$  plate of  $\overline{Au}/\overline{Cu}_2O/fl-G$  (0.32 mg Au/Cu of 3/1), 5mg  $Au(0.52 \text{ wt } \%) / fl-G$  8 mL  $H_2O$  deionized, temperature: RT; time 18h. Note: Conversion refers to Michael donor transformation. Conversion and selectivities were determined by GC-MS.

However, for NaOH, and  $\overline{Au}/fl-G$ , and  $\overline{Cu}_2O/fl-G$  films this increase corresponded to a further decrease of the selectivity to MA1 (Table 1, entries 5, 6 and 7). Interestingly, the increase of the conversion for the bimetallic  $\overline{Au}/\overline{Cu}_2O/fl-G$  films catalyst did not affect the selectivity in MA1, which on the contrary becomes total. This behavior can be related to the different basic properties of  $\overline{Au}/\overline{Cu}_2O/fl-G$  in comparison to those of  $\overline{Cu}_2O/fl-G$  or  $\overline{Au}/fl-G$  films.

Indeed the  $CO_2$  chemisorption on these catalysts results in different concentrations of basic sites and  $CO_2$  desorption temperatures (Table 2). These results correspond to values resulted after the subtraction of the  $CO_2$  directly chemisorbed by the graphene support [44].

**Table 2.**  $CO_2$  chemisorption results

Sample	Temperature at Maximum ( $^{\circ}C$ )	Adsorbed $CO_2$ (mmoles/g) $\times 10^{-3}$
$Au/fl-G$	346	2.78
$Cu_2O/fl-G$	292	2.20
$Au/Cu_2O/fl-G$	350	0.94
	252	6.29
	347	3.99

The concentration of the basic sites decreased in the order  $\overline{Au}/\overline{Cu}_2O/fl-G > \overline{Cu}_2O/fl-G > \overline{Au}/fl-G$  while the strength of these sites, appreciated from the  $CO_2$  desorbed at around  $350^{\circ}C$  in the order  $\overline{Au}/\overline{Cu}_2O/fl-G > \overline{Au}/fl-G > \overline{Cu}_2O/fl-G$ . These results are in line with the catalytic data included in the Table 1 supporting the role of the basicity in this reaction.

**Table 3.** Time evolution of the conversion and selectivity to MA1 and MA2 for  $\overline{Au}/fl-G$ , NaOH and  $\overline{Au}/\overline{Cu}_2O/fl-G$  in the Michael addition of MeAcOAc donor with MVK acceptor.

Nr. crt	Time (h)	Catalyst	Conversion (%)	Selectivity, (%) MA1	Selectivity (%) MA 2	TON
1		$Au/fl-G$	14.3	92.6	7.4	$1.27 \times 10^5$
2	5	$\overline{Cu}_2O/fl-G$	12.8	93.5	6.5	$0.41 \times 10^5$
3		$\overline{Au}/\overline{Cu}_2O/fl-G$	68.9	88.4	11.6	$1.43 \times 10^7$
4		$Au/fl-G$	2.3	100.0	0	1.74
5		NaOH	84.9	28.8	71.2	7.07
6		$Au/fl-G$	21.7	85.2	14.8	
7	9	$\overline{Cu}_2O/fl-G$	19.4	86.6	13.4	

8		$\overline{Au}/\overline{Cu_2O}/fl-G$	73.4	81.6	18.4
9		NaOH	100	22.4	77.6
10		$\overline{Au}/fl-G$	32.4	75.7	24.3
11	18	$\overline{Cu_2O}/fl-G$	31.1	77.4	23.6
12		$\overline{Au}/\overline{Cu_2O}/fl$	85.8	72.8	17.2
13		NaOH	100	12.7	87.3
14		$\overline{Au}/fl-G$	44.4	74.5	24.5
15	30	$\overline{Cu_2O}/fl-G$	42.5	75.7	24.3
16		$\overline{Au}/\overline{Cu_2O}/fl$	89.9	71.5	18.5
17		NaOH	100	7.0	93.0

Reaction conditions: Michael donor: 1 mmol: Methylacetoacetate (MeAcOAc), Michael acceptor: 1.5 mmoles, Catalyst: 0.12 mmoles NaOH or 1 piece of  $\overline{Au}/fl-G$ , or 5 mg  $\overline{Au}/fl-G$ , solvent: 8 mL  $H_2O$  deionized, temperature: RT; Note: Conversion refers to Michael donor transformation. Conversion and selectivities were determined by GC-MS.

In order to better understand the kinetics of the Michael addition we measured the conversion and the selectivity in the Michael addition of MeAcOAc donor with MVK acceptor using NaOH, and the  $\overline{Au}/fl-G$ ,  $\overline{Cu_2O}/fl-G$ ,  $\overline{Au}/\overline{Cu_2O}/fl-G$  film catalysts at different reaction times. The results are listed in Table 3. With NaOH as catalyst the conversion becomes total after 5h. Further increase of the reaction time till 30h corresponded to a continuous deplete in the selectivity to MA1 in the favor to MA2 (93% selectivity), which is a typical behavior for a strong basic medium leading to a second addition. In terms of conversion, the monometallic  $\overline{Au}/fl-G$  and  $\overline{Cu_2O}/fl-G$  film catalysts provided much smaller conversions and better selectivities to MA1. Surprisingly was the behavior of the  $\overline{Au}/\overline{Cu_2O}/fl-G$  film which allowed indeed very good conversions but also selectivity to MA1 even after 30h.

However, the calculation of the TONs after 5h showed a different order in activity than that presented in the Table 3.  $\overline{Au}/\overline{Cu_2O}/fl-G$  exhibits an almost seven times higher TON order than NaOH while  $\overline{Au}/fl-G$  and  $\overline{Cu_2O}/fl-G$  film catalysts almost five times. These values confirm, like in other coupling reactions the extremely high activity of the orientated metal nanoparticles [31, 33]. Unoriented supported  $\overline{Au}/fl-G$  nanoparticle catalysts were much less active compared to  $\overline{Au}/fl-G$  (five order difference in activity). However, in terms of TONs the activity of these nanoparticles is comparable to that of NaOH, namely, still high.

#### Comparative behavior of $\overline{Au}/fl-G$ , $\overline{Cu_2O}/fl-G$ and $\overline{Au}/\overline{Cu_2O}/fl-G$ films in the Henry addition

The Henry addition (Scheme1, Eq. 2) has been investigated in the presence of the same  $\overline{Au}/fl-G$ ,  $\overline{Cu_2O}/fl-G$  and  $\overline{Au}/\overline{Cu_2O}/fl-G$  film catalysts. This reaction is generally catalyzed by many organic bases, including carbonates, bicarbonates, alkali metal

hydroxides, alkoxides, and organic nitrogen bases with the disadvantage of the difficulty in separation of various by-products [45]. Under basic conditions nitroalkanes are able to deprotonate the nitroaldol leading to a nitronate anion intermediate [46] which further reacts with aldehydes yielding  $\beta$ -nitroalcohols [47]. Table 4 summarizes the catalytic results on the investigated catalysts.

As Table 4 shows, using 2 mmoles of  $K_2CO_3$  as a weak inorganic base, the reaction took place with a moderate conversion, but with a relatively high selectivity to the nitroaldol product. TON value calculated under these conditions was of 0.15. On the contrary, in the presence of  $\overline{Au}/fl-G$  and  $\overline{Cu_2O}/fl-G$ , although the conversions were smaller, in terms of activity, these catalysts presented much higher TONs. They increased till the order of  $10^4$ . Importantly, an increase of the temperature from RT to  $50^\circ C$  led to a further increase of the TON with one order of magnitude. The reaction by-product in these reactions was benzoic acid. For  $\overline{Cu_2O}/fl-G$ , in addition, benzaldehyde was further oxidized to benzoic acid which becomes the major by-product. Non-orientated  $\overline{Au}/G$  and  $\overline{Cu_2O}/G$  catalysts showed even higher TONs than the corresponding orientated catalysts that might be an evidence of an increased activity of the smaller particles.

**Table 4.** Catalytic efficiency of  $\overline{Cu_2O}/fl-G$ ,  $\overline{Au}/fl-G$  and  $\overline{Au}/\overline{Cu_2O}/fl-G$  films as catalysts in the Henry reaction

Nr. crt	Solvent	Catalyst	Conversion <sup>a</sup> (%)	Selectivity to nitroaldol (%)	TON
1 <sup>b</sup>	no	$K_2CO_3$	59.8	91.8	0.15
2	no	$\overline{Au}/fl-G$	0	0	0
3 <sup>c</sup>	IPA	$\overline{Au}/fl-G$	11.1	32.0	$4.6 \times 10^4$
4	IPA	$\overline{Au}/fl-G$	64.7	46.2	$2.7 \times 10^5$
5 <sup>e</sup>	IPA	$Au(0.15wt\%/G)^*$	33.6	54.0	$4.4 \times 10^6$
6	no	$\overline{Cu_2O}/fl-G$	0	0	0
7	Heptane	$\overline{Cu_2O}/fl-G$	0	0	0
8 <sup>e</sup>	IPA	$\overline{Cu_2O}/fl-G$	7.9	30.2	$1.2 \times 10^4$
9	IPA	$\overline{Cu_2O}/fl-G$	74.5	60.4	$1.2 \times 10^5$
10	IPA	$Cu_2O(1 wt\%/G)^{**}$	89.3	0.3	$8.9 \times 10^5$
11	no	$\overline{Au}/\overline{Cu_2O}/fl-G$	0	0	0
12	Heptane	$\overline{Au}/\overline{Cu_2O}/fl-G$	90.9	0.1	$9.4 \times 10^6$
13	IPA	$\overline{Au}/\overline{Cu_2O}/fl-G$	97.4	96.7	$1.0 \times 10^7$

Reaction conditions: 10 mmoles  $MeNO_2$ , 0.5 mmoles benzaldehyde, 24h,  $50^\circ C$ , 3mL solvent; catalyst: <sup>a</sup>conversion for benzaldehyde; <sup>b</sup>2 mmoles of  $K_2CO_3$ ; <sup>c</sup>RT; catalyst: 1 piece of  $1 \times 1 cm^2$  of  $\overline{Cu_2O}/fl-G$  on quartz (0.20 mg of Cu total), or one piece of  $1 \times 1 cm^2$  plate of  $\overline{Au}/fl-G$  film (0.24 mg of Au total) or one piece of  $1 \times 1 cm^2$  plate of  $\overline{Au}/\overline{Cu_2O}/fl-G$  (0.32 mg Au/Cu of 3/1) or <sup>e</sup>5mg  $Au(0.15 wt\%/G)$ ; or <sup>\*\*</sup>5mg  $Cu(1 wt\%/G)$ ; Difference to 100% in selectivity is for benzoic acid. Conversion and selectivity were determined by GC-MS.

However, like for the Michael addition the bicomponent  $\overline{Au}/\overline{Cu_2O}/fl-G$  films led to the best performances. Very high TONs and

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selectivities were achieved with this catalyst. Under the optimal reaction conditions of 50°C for 24 h, they afforded an as high conversion of benzaldehyde as 97.4 % and a selectivity of 96.7 % in favor of nitroaldol.

Very important to notice, the catalysts were recycled five times with almost no changes in the catalytic behavior.

The role of the solvent in this reaction is very important. In an aprotic solvent such as heptane the conversions were either zero or the reaction was directed to benzaldehyde. It is assumed that the measured basicity is the combined effect of the very small particle size of these films and the generated interaction between these and the graphene support.

The behavior of these catalysts in both Michael and Henry reactions should be associated to their properties as Lewis base. In Cu<sub>2</sub>O oxide Cu(I) exhibits a d<sup>10</sup> configuration [48] and basicity is associated to the presence of surface O<sup>2-</sup> species. Au has also a d<sup>10</sup> configuration and this property affords an increase of the basicity of the supported metal nanoparticles with direct catalytic effect [49]. On this basis the behaviour of the individual Cu<sub>2</sub>O and Au/graphene catalysts as bases is well justified according to the literature.

The increase of the activity of bicomponent Cu<sub>2</sub>O-Au/graphene catalyst should be the result of the direct interaction of Au with Cu<sub>2</sub>O. Recent studies of Glorius et al. [49], using gold deposited on CeO<sub>2</sub>-ZrO<sub>2</sub>-mixed oxides have shown that the density of acid sites was decreased, whereas the density of basic site was increased by modification with Au. A similar effect can result after the interaction with Cu<sub>2</sub>O. This effect is more evident for the experiment described in entry 12.

Such a model is also supported by the results from Table 4 presenting the effect of the solvent. Heptane is not able to suppress the acidity induced by the two active species. On the contrary, IPA has two contributions in this reaction: i) to act as a solvent for the investigated substrates, and ii) to block any residual Lewis acidity. This effect is more evident for the catalysts containing Cu<sub>2</sub>O which reached conversions of 97.4% and TONs of 10<sup>7</sup>.

## Conclusions

In summary, we have developed a simple and efficient procedure for Michael and Henry addition reactions using bimetallic nanoplatelets grafted onto few-layers graphene  $\overline{Au}/\overline{Cu_2O}$  /fl-G films as catalyst. These reactions occurred in the absence of any

extrinsic base. Moreover, films of  $\overline{Au}$  and  $\overline{Cu_2O}$  /fl-G also exhibit a high catalytic activity to promote the Michael addition of acyclic active methylene and methine compounds to  $\alpha$ ,  $\beta$ -conjugated ketone or the Henry reaction of nitroalkane to  $\beta$ -nitroaldols. Noteworthy, by comparison to homogeneous NaOH or K<sub>2</sub>CO<sub>3</sub>, in the presence of the heterogeneous catalysts these reactions occurred with TONs at least four orders of magnitude higher. While the homogeneous catalysts provided TONs close to the unity for  $\overline{Au}/\overline{Cu_2O}$  /fl-G this was of the order of 10<sup>7</sup>. Un-oriented supported nanoparticles Au/fl-G catalysts were much less active compared to  $\overline{Au}$ /fl-G. However, in terms of TONs the activity of these nanoparticles is comparable to that of NaOH, namely, still high. These performances are in line with the basicity of these catalysts demonstrated from CO<sub>2</sub> chemisorption measurements. The effect of the nano-size and the interaction of the nanoparticles with the graphene is also important to achieve these properties.

## Experimental Section

### General procedure for the Michael addition.

To a solution of  $\beta$ -ketoesters as Michael donor (1 mmol of methyl acetoacetate or ethyl acetoacetate) in 8 mL of solvent (deionized H<sub>2</sub>O) was added MVK as Michael acceptor (1.5 mmoles, 0.105 g), base (0.12 mmoles, NaOH) if required and one piece of 1 × 1 cm<sup>2</sup> plate of  $\overline{Cu_2O}$ /fl-G on quartz (0.24 mg of Cu total), one piece of 1 × 1 cm<sup>2</sup> plate of  $\overline{Au}$ /fl-G film or one piece of 1 × 1 cm<sup>2</sup> plate of  $\overline{Au}/\overline{Cu_2O}$ /fl-G films as catalysts. The resulting mixture was left stirring at room temperature for 5-30 h. The reaction mixture was then filtered, extracted with ethyl acetate (3 × 10 mL) and the combined organic layer was dried over Na<sub>2</sub>SO<sub>4</sub>, filtered and concentrated.

### Product analysis

Irrespective of reaction procedure, after reaction the catalyst was collected by filtration or was manually removed, and the reaction products were analyzed and identified by GC-MS (THERMO Electron Corporation instrument), Trace GC Ultra and DSQ, Trace GOLD with a TG-5SiIMS column (30 m × 0.25 mm × 0.25 mm). GC-MS analysis of the reaction products using *Methyl acetoacetate* corresponded to:

**MA1:** Methyl 2-acetyl-5-oxohexanoate: GC-MS, (m/z): 186 (M<sup>+</sup>, 2), 155 (12), 154 (12), 144 (100), 143 (18), 139 (25), 129 (15), 116 (40), 112 (56), 111 (57), 101 (21), 97 (17), 87 (64), 84 (64), 69 (17), 58 (20), 55 (29).

**MA2:** GC-MS, (m/z): 256 (M<sup>+</sup>, 1), 238 (20), 196 (24), 186 (87), 182 (15), 181 (66), 179 (87), 167 (48), 165 (22), 164 (42), 154 (88), 153 (63), 143 (43), 139 (82), 137 (33), 136 (40), 129 (90), 125 (33), 123 (73), 116 (47), 111 (100), 109 (56), 97 (63), 95 (32), 93 (65), 91 (23), 85 (18), 84 (12), 79 (14), 71 (32), 55 (25). and for ethyl acetoacetate to:

**MA1:** Ethyl 2-acetyl-5-oxohexanoate: GC-MS, (m/z): 200 (M<sup>+</sup>, 2), 158 (100), 139 (29), 130 (30), 112 (59), 111 (69), 101 (55), 84 (71), 73 (33), 55(17).

**MA2:** GC-MS, (m/z): 270 (M<sup>+</sup>, 1), 252(18), 209 (24), 200 (100), 181 (98), 179 (88), 167 (52), 165 (32), 164 (30), 157 (39), 154 (55), 153(25), 143(76), 139 (91), 137 (29), 136 (31), 125 (29), 123 (60), 121 (54), 115 (16), 111 (90), 109 (52), 97 (43), 95 (27), 93 (51), 71 (16), 55 (14).

#### General procedure for the Henry reaction.

All reagents were purchased from Sigma-Aldrich and used as received without further purification. To a glass sealed vial containing a magnetic stir bar with 3 mL of solvent (Isopropyl alcohol dried (IPA) or heptane) was added benzaldehyde (0.5 mmoles), nitromethane (10 mmoles) and catalyst. Resulting mixture was left stirring for 24h at room temperature or 50°C. The reaction mixture was then filtered, concentrated and silylated. The products were analyzed and identified by using GC-MS (THERMO Electron Corporation instrument) and a Bruker Advance III UltraShield 500 MHz spectrometer, operating at 500,13 MHz for <sup>1</sup>H NMR, 125,77 MHz for <sup>13</sup>C NMR. For <sup>1</sup>H NMR were reported downfield from CDCl<sub>3</sub> (δ: 7.26ppm) and for <sup>13</sup>C NMR chemical shifts were reported in the scale relative to the solvent of CDCl<sub>3</sub> (δ: 77.0 ppm) used as an internal reference.

The recovered products were silylated (50 μL pyridine, 100 μL BSTFA (*N,O*-bis(trimethylsilyl) trifluoroacetamide) and TMCS (trimethylchlorosilane) silane agent), and analyzed by GC-MS. The identification of the products was made using a GC-MS (THERMO Electron Corporation instrument), Trace GC Ultra and DSQ, Trace GOLD: TG-5SiIMS column with the following characteristic: 30m x0.25mm x 0.25um working with a temperature program (50 °C (2 min) to 250 °C at 10 °C/min (Hold 10.00 min) for a total run time of 32 min) at a pressure of 0.38 Torr with He as the carrier gas.

NMR analysis of 1-(4-methoxyphenyl)-2-nitroethanol corresponded to:

<sup>1</sup>H NMR (CDCl<sub>3</sub>) δ = 7.54-7.48 (m, 5H, H<sub>Ph</sub>), 5.49-5.47 (dd, 1H, CHOH), 4.63-4.51 (m, 2H, CH<sub>2</sub>NO<sub>2</sub>), 3.82 (s, 3H), 3.92 (br s, 1H, OH) ppm.

<sup>13</sup>C NMR (CDCl<sub>3</sub>) δ = 138.10 (C<sub>Ph</sub>), 129.25 (2C, CH<sub>Ph</sub>), 129.14 (CH<sub>Ph</sub>), 125.93(2C, CH<sub>Ph</sub>), 81.23 (2C, CH<sub>2</sub>NO<sub>2</sub>), 71.04 (CHOH) ppm.

#### Synthesis of catalysts

$\overline{Au}/\overline{f\text{-}G}$  and  $\overline{Cu_2O}/\overline{f\text{-}G}$  catalysts were prepared according to previous reports [9, 11]. Preparation of  $\overline{Au}/\overline{Cu_2O}/\overline{f\text{-}G}$  was carried out following a close procedure. Alginate (0.5 g) from Aldrich (low molecular weight) was dissolved in a copper (II) nitrate aqueous solution (420 mg of Cu(NO<sub>3</sub>)<sub>2</sub>·2 H<sub>2</sub>O in 25 ml of water). 0.23 g of acetic acid was added to dissolve alginate completely. The solution was filtered through a syringe having a 0.45 μm diameter pore size membrane filter to remove any impurity that could be present in commercial alginate. The films were supported on a quartz plate (2 × 2 cm<sup>2</sup>) by casting 300 μl of filtered solution spinning at 4,000 rpm. for 1 min. Subsequently, films were immersed into a 1 mM aqueous solution of NaAuCl<sub>4</sub> (Aldrich) during 1 min to adsorb Au on Cu-containing alginate film, before proceeding to pyrolysis. The pyrolysis was performed under argon atmosphere (1 mlx min<sup>-1</sup>) in a tubular oven at 5 °C·min<sup>-1</sup> temperature increase rate up to 900 °C that was maintained for 2 h. The sample was, then, cooled at room temperature under argon. The resulting sample immediately after the pyrolysis consisted in an alloy of Au and Cu nanoplatelets grafted on G.

Preparation and analytic characterisation of un-oriented supported Au/f-G nanoparticles was carried out following the procedure described in [31]. The content of gold determined by ICP-OES was of 0.52 wt%.

#### Catalysts characterization

CO<sub>2</sub>- and NH<sub>3</sub>-TPD measurements were carried out using the same AutoChem II 2920 station. The samples (3–5mg), placed in a U-shaped quartz reactor with an inner diameter of 0.5cm, were pretreated under He (Purity 5.0, from Linde) at 120°C for 1h and then exposed to a flow of NH<sub>3</sub> or CO<sub>2</sub> (from SIAD) for 1h. After that, the sample was purged with a flow of He (50ml min<sup>-1</sup>) for 20 min at 25°C in order to remove the weakly adsorbed species. TPD was then started, with a heating rate of 10°C / min till 850°C. The desorbed products were analyzed with a TC detector. The desorbed NH<sub>3</sub> or CO<sub>2</sub>, expressed as mmols per grams of catalyst, was determined using a calibration curve.

RAMAN spectroscopy. Raman spectra were acquired using a Labram-HR (Horiba Jobin Yvon) Raman spectrometer (600 mm<sup>-1</sup> grating, 100 μm entrance slit) coupled to a Peltier-cooled CCD detector (Andor DU420) and an Olympus BXF optical microscope. Raman scattering was excited at 632.8 nm by means of a He Ne laser with 0.1-mW excitation power on the sample.

The laser beam was focused on the sample via a long-working distance x 50 microscope objective (numerical aperture 0.5), which served also to collect the scattered photons. The Rayleigh scattering was removed by a holographic notch filter and the Raman spectra were recorded between 200 and 2,000 cm<sup>-1</sup>.

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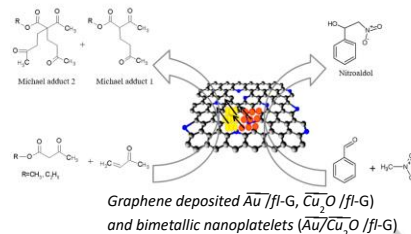
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Michael and Henry addition reactions have been investigated using mono ( $\overline{\text{Au}}$  and  $\overline{\text{Cu}_2\text{O}}$  /fl-G) and bimetallic nanoplatelets ( $\overline{\text{Au/Cu}_2\text{O}}$  /fl-G) grafted onto few-layers graphene films as heterogeneous catalysts. These reactions occurred in the absence of any extrinsic base with TONs at least four orders of magnitude higher.

**Graphene, Coupling reactions**

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**Bimetallic Oriented ( $\overline{\text{Au/Cu}_2\text{O}}$ ) versus monometallic 1.1.1  $\overline{\text{Au}}$  (0) or 2.0.0  $\overline{\text{Cu}_2\text{O}}$  Graphene supported Nano-platelets as very efficient Catalysts for Michael and Henry Additions**