

Surface acoustic waves as an energy source for drop scale synthetic chemistry†

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A new modality for chemical synthesis on a drop scale which employs a piezoelectric chip as the reactor and surface acoustic waves (SAWs) as the source of energy (and consequent heating) is described.

With the advent of new microreactor technologies much of the emphasis has been on continuous flow microfluidics in channels. A lesser, although still significant, emphasis has been placed on drop- or droplet-based microfluidics for chemical reactors.¹ In this paper we introduce a new modality for chemical synthesis on a drop scale which employs a piezoelectric chip as the reactor and surface acoustic waves (SAWs) as the source of energy. Reaction mixtures are simply applied as drops onto an appropriate surface and reacted for short periods of time.

Wortman *et al.* have proposed a SAW device for promoting chemical reactions involving heterogeneous catalysis, though no real examples were provided.² Shiohara and co-workers have reported the use of a SAW device as a thermal recycler, a device which can heat up liquids, and concluded that SAW-streaming was mainly responsible for the heating.³

The device consists of a piezoelectric substrate, in this case a 127.86 y-x cut single lithium niobate (LN) crystal, with interdigital transducers (IDTs) in the form of 250 nm thick Ti-Al electrodes patterned at each end using standard photolithography onto the LN substrate (Fig. 1).⁴ The surface acoustic waves, 10 nm amplitude electroacoustic flexural waves that propagate along the surface of the substrate, are generated by applying an oscillating electric field to the IDTs.⁵ An electric field is formed in the substrate between the IDT electrodes causing strains due to the piezoelectric effect, which, in turn, produce undulating deformations along the surface. The spacing between the IDTs defines the SAW frequency which was set at 20 MHz for this study. In principle a frequency range of ~1 MHz to >2 GHz is available with this technology.

The LN substrate employed had a 500 nm thick coating of Teflon[®] AF, except for a circular region at the centre of the substrate with bare LN, 5 mm in diameter and commensurate with the drop dimension. The drop was placed on this exposed circular region of the LN substrate, the Teflon[®] AF coating acted to retain the drop during the application of the SAWs.

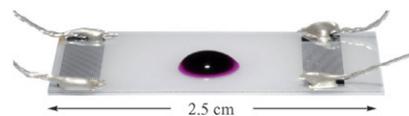
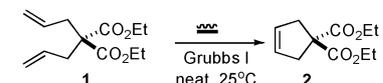
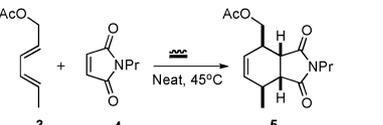
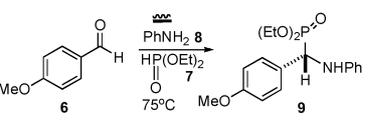
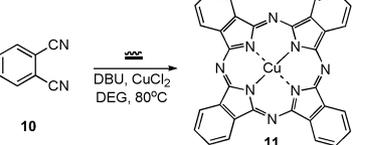
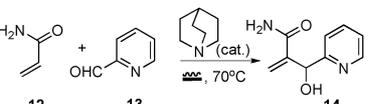


Fig. 1 Photo of a ~40 μ L drop on a piezoelectric substrate with IDTs at either end of the device connected to a power source. The inputs are connected to an amplified sine wave generator. When the power is supplied the SAW travels on the substrate surface from one IDT to the other underneath the drop generating a standing wave.

The experimental procedure was simple. A 40 μ L drop of reaction mixture (~30–40 mg) was pipetted onto the LN piezoelectric substrate between the IDTs (Fig. 1) and completely within the path of the SAW radiation defined by the width of the IDT finger electrodes. When input power was applied, the drop was observed to vibrate vigorously if the viscosity of the reaction mixture was low. If the viscosity was significantly higher than that of typical organic solvents, an internal streaming pattern could be observed. SAW irradiation continued until the reaction was complete (analytical TLC). Reactions could be run neat (Table 1, entries 1–3 and 5) or in relatively non-volatile solvents (entry 4).

Table 1 Results from drop scale SAW () irradiated chemical reactions

Entry	Reaction	Yield (%)	Time/min
1		>99	<2
2		74	30
3		98	4.5
4		52	15
5		86	15

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In most cases the temperature of the irradiated reaction mixture rapidly increased (entries 2–5). Clear evidence that the SAWs were responsible for heating the liquid reactants came from application of cooling to the LN substrate (by placing it on an ice-cooled aluminium block or a Peltier device). Under these conditions irradiation with SAWs caused an increase in temperature of the reaction drop to approximately +42 °C, whilst the LN substrate remained at ~ +8 °C.

For this study we chose several mechanistically distinct classes of reactions in order to examine the scope of the new technology when applied to a surface rather than in a reaction flask. The results are summarised in the Table. In entry 1⁶ a mixture of **1** and 4 mol% of Grubbs Gen I catalyst was subjected to SAWs (at 4 W) for two minutes with the temperature maintained at approximately 25 °C (employing a Peltier device). This gave essentially quantitative conversion to cyclopentene **2**. The progress of this reaction was easily monitored by observing the bubbling due to the evolution of ethylene, a by-product of the metathesis process. Entry 2 summarises our results from a Diels–Alder reaction recently published by Sharpless and co-workers.⁷ This example was chosen partly because the reactants are not too volatile. Although conversion was complete after 30 minutes isolated yields were less than quantitative due to a small amount of material loss.

The third entry in the Table shows the results for a Kabachnik–Fields reaction.⁸ We have successfully conducted many such reactions but only include one representative example in this communication. We observed rapid imine formation followed by a slightly slower addition of the phosphite. In the fourth example we examined the synthesis of Cu(II)phthalocyanine. This has been prepared previously by refluxing an ethanolic solution of phthalonitrile, Cu(II)Cl₂ and DBU.⁹ Employing the less volatile diethylene glycol as solvent, we found that the reaction proceeds well in only 15 minutes at 80 °C. Product formation was easily observed as the green solution rapidly changes to a suspension of blue solid product. The moderate yield is mainly due to difficulties in product isolation rather than the efficiency of the process itself. In the final example (entry 5) we chose a Baylis–Hillman reaction with acrylamide, a problematic reactant in this process (acrylamide is reportedly only reactive¹⁰ under high pressure conditions or using water/dioxane with DABCO as catalyst¹¹ or methanol with quinuclidine as catalyst¹²), and found that the reaction, employing quinuclidine was clean and fast.

All reactions in the Table, employing alternative energy sources, have been reported to require far longer reaction times and, in the case of ultrasound and microwaves, far higher power. However, all these reports were on relatively large scale reactions and none has been reported on a drop scale. Consequently, each of the processes in this study was also run at exactly the same scale as those for our SAW experiments but without SAW irradiation. We found that these drop scale reactions, which were simply heated to the same temperatures as those in Table 1, proceeded at similar rates to those observed during the SAW-based experiments. Thus the speed of these reactions can, most likely, be ascribed to the temperature as well as the scale.

In conclusion we have demonstrated that the use of surface acoustic waves shows great potential as a new modality for energy input into chemical reactions at drop scales. In general, reactions are fast, yields are high and the products are clean. When combined with the well-established ability of SAWs to actuate drops,¹³ our results lay the foundation for a powerful new approach to the manipulation and processing of chemicals. The necessary components (wave generator, amplifier, configured substrates) are readily accessible from commercially available sources. All results reported here for SAW-irradiated experiments were run at a fixed frequency of 20 MHz. Other frequencies (up to 2 GHz) as well as other device configurations, including arrays, are available or under development and the effect of these variations on the outcome of chemical reactions will be reported soon.

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