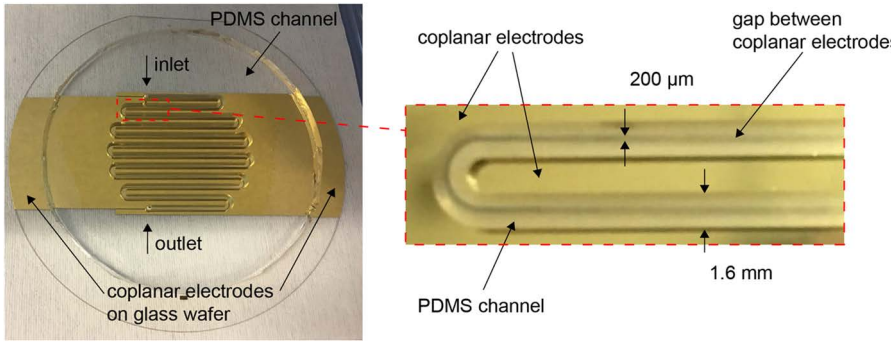


**Figure 7.19** Microfluidic device enabling electric-field-assisted protein crystallization in continuous flow. A low-voltage AC electric field is placed over the co-planar electrodes to enhance the crystallization process. Reprinted with permission from ref. 292, Copyright 2016 American Chemical Society.

### 7.5.3 Microwave Fields

The use of microwave irradiation allows for the rapid heating of a process medium and the manipulation of crystal nucleation and growth kinetics by increasing mass transfer phenomena, which has been widely applied for chemical reactions and in equipment for microwave-assisted processing in continuous flow.[296,297] Microwaves enhanced mass transfer in an MSMPR crystallizer for crystallization of magnesium carbonate from water, which increased the nucleation rate and crystal growth rate.[298] Rodríguez-Clemente and Gómez-Morales[299] studied the reactive crystallization of calcium carbonate from aqueous solution in an MSMPR crystallizer. The crystallizer was made out of microwave transparent PTFE and placed inside a microwave furnace in such a way that the feed and product could be transferred easily. They found that microwaves did not have a significant effect on crystal growth, but that the nucleation rate was several orders of magnitude higher if microwave irradiation was used. Furthermore, steady state was reached faster with microwave irradiation (within 2–3 residence times instead of within 6–10 residence times for a conventional MSMPR crystallizer). This effect was explained with the enhanced nucleation rate by a faster dehydration of the hydration shell of the cations, which is known to be a rate-limiting step for the precipitation of calcium carbonate. A similar mechanism was considered responsible for the observation that microwaves provided increased control over the polymorphic form of calcium carbonate.[300]

Similarly as for the application of ultrasound, the penetration depth of microwaves is limited to a few centimeters,[297] therefore, flow cells may be needed to obtain a uniform irradiation and to avoid hot spot formation. Kacker *et al.*[301] used a custom-made circulation loop through a microwave cavity (Figure 7.20) for fines dissolution during a batch cooling crystallization of paracetamol from isopropanol.